ASME PTC 13-2018

Wire-to-Air Performance Test Code for Blower Systems

Performance Test Codes

AN AMERICAN NATIONAL STANDARD

The American Society of Mechanical Engineers

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Two Park Avenue • New York, NY • 10016 USA

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CONTENTS

Mandatory Appendix

Nonmandatory Appendices

Figures

Tables

NOTICE

All Performance Test Codes must adhere to the requirements of ASME PTC 1, General Instructions. The following information is based on that document and is included here for emphasis and for the convenience of the user of the Code. It is expected that the Code user is fully cognizant of Sections 1 and 3 of ASME PTC 1 and has read them prior to applying this Code.

ASME Performance Test Codes provide test procedures that yield results of the highest level of accuracy consistent with the best engineering knowledge and practice currently available. They were developed by balanced committees representing all concerned interests and specify procedures, instrumentation, equipment-operating requirements, calculation methods, and uncertainty analysis.

When tests are run in accordance with a code, the test results themselves, without adjustment for uncertainty, yield the best available indication of the actual performance of the tested equipment. ASME Performance Test Codes do not specify means to compare those results to contractual guarantees. Therefore, it is recommended that the parties to a commercial test agree before starting the test and preferably before signing the contract on the method to be used for comparing the test results to the contractual guarantees. It is beyond the scope of any code to determine or interpret how such comparisons shall be made.

FOREWORD

The American Society of Mechanical Engineers (ASME) has a long history of developing and publishing test codes for blowers and compressors. The predecessor to the Test Code for Displacement Compressors, Vacuum Pumps, and Blowers, now designated as ASME PTC 9, was originally issued in 1915. The Test Code for Compressors and Exhausters, ASME PTC 10, was originally issued in 1934, followed by several editions.

The technology of blowers, compressors, and ancillary components has advanced since the last revisions of these codes. The developments have included new types of blower and compressor mechanisms, new techniques for control and modulation, and the widespread commercialization of packages with all the mechanical and electrical components required for a fully operable system combined in an integrated factory-assembled unit. The wide application of variable speed motor control and close-coupled motors and blowers were especially problematic in the application of the earlier performance and power test codes.

The electric power industry and the wastewater treatment industry were particularly concerned by the inadequacies of the earlier codes in predicting and confirming energy consumption of the systems used to provide low-pressure air to the wastewater treatment process.

In 2010 the Consortium for Energy Efficiency (CEE) approached ASME and several individuals with the suggestion that a new performance test code be developed. This Code intends to incorporate the following features:

(a) technology neutral evaluation, to allow direct comparison of various blower systems

(b) wire-to-air power consumption, to allow convenient prediction of on-site energy requirements

(c) industry acceptance, with rigorously developed and credible procedures for the test itself and related calculation methodologies

This new Code, ASME PTC 13, Wire-to-Air Performance Test Code for Blower Systems, is the result of many hundreds of hours of dedicated work by professionals from a broad cross-section of industries involved in the manufacture and application of blowers. The needs of the wastewater treatment industry were important in the development of the Code, but it is anticipated that the Code can be used for any application of low-pressure air blowers.

The contents of this Code are comprehensive. The intent is that the required test procedures and instrumentation techniques can be implemented solely by the use of this Code. Many other ASME codes are referenced to permit examination of various test aspects in greater detail if necessary. This Code quantifies the statistical uncertainty of the measurements and provides rigorous examples to follow.

The members of the PTC 13 Committee would like to thank all of the participants in the development of this Performance Test Code. This includes many individuals outside the Committee who provided expertise and guidance, without which this work could not have been completed. Particular thanks go to Mr. John Oleyar, the founding chair of the Committee, and to Jack Karian, the ASME Staff Secretary who guided and assisted the Committee through the most critical stages.

This Standard is available for public review on a continuing basis. This provides an opportunity for additional public input from industry, academia, regulatory agencies, and the public-at-large.

ASME PTC 19.1-2018 was approved by the PTC Standards Committee on January 3, 2018, and was approved as an American National Standard by the ANSI Board of Standards Review on July 20, 2018.

ASME PTC
ASME PTC COMMITTEE

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General. ASME Standards are developed and maintained with the intent to represent the consensus of concerned interests. As such, users of this Standard may interact with the Committee by requesting interpretations, proposing revisions or a case, and attending Committee meetings. Correspondence should be addressed to:

Secretary, PTC Standards Committee
The American Society of Mechanical Engineers
Two Park Avenue
New York, NY 10016-5990
http://go.asme.org/Inquiry

Proposing Revisions. Revisions are made periodically to the Standard to incorporate changes that appear necessary or desirable, as demonstrated by the experience gained from the application of the Standard. Approved revisions will be published periodically.

The Committee welcomes proposals for revisions to this Standard. Such proposals should be as specific as possible, citing the paragraph number(s), the proposed wording, and a detailed description of the reasons for the proposal, including any pertinent documentation.

Proposing a Case. Cases may be issued to provide alternative rules when justified, to permit early implementation of an approved revision when the need is urgent, or to provide rules not covered by existing provisions. Cases are effective immediately upon ASME approval and shall be posted on the ASME Committee web page.

Requests for Cases shall provide a Statement of Need and Background Information. The request should identify the Standard and the paragraph, figure, or table number(s), and be written as a Question and Reply in the same format as existing Cases. Requests for Cases should also indicate the applicable edition(s) of the Standard to which the proposed Case applies.

Interpretations. Upon request, the PTC Standards Committee will render an interpretation of any requirement of the Standard. Interpretations can only be rendered in response to a written request sent to the Secretary of the PTC Standards Committee.

Requests for interpretation should preferably be submitted through the online Interpretation Submittal Form. The form is accessible at http://go.asme.org/InterpretationRequest. Upon submittal of the form, the Inquirer will receive an automatic e-mail confirming receipt.

If the Inquirer is unable to use the online form, he/she may mail the request to the Secretary of the PTC Standards Committee at the above address. The request for an interpretation should be clear and unambiguous. It is further recommended that the Inquirer submit his/her request in the following format:

Subject:	Cite the applicable paragraph number(s) and the topic of the inquiry in one or two words.
Edition:	Cite the applicable edition of the Standard for which the interpretation is being requested.
Question:	Phrase the question as a request for an interpretation of a specific requirement suitable for general understanding and use, not as a request for an approval of a proprietary design or situation. Please provide a condensed and precise question, composed in such a way that a “yes” or “no” reply is acceptable.
Proposed Reply(ies):	Provide a proposed reply(ies) in the form of “Yes” or “No,” with explanation as needed. If entering replies to more than one question, please number the questions and replies.
Background Information:	Provide the Committee with any background information that will assist the Committee in understanding the inquiry. The Inquirer may also include any plans or drawings that are necessary to explain the question; however, they should not contain proprietary names or information.

Requests that are not in the format described above may be rewritten in the appropriate format by the Committee prior to being answered, which may inadvertently change the intent of the original request.

Moreover, ASME does not act as a consultant for specific engineering problems or for the general application or understanding of the Standard requirements. If, based on the inquiry information submitted, it is the opinion of the Committee that the Inquirer should seek assistance, the inquiry will be returned with the recommendation that such assistance be obtained.

ASME procedures provide for reconsideration of any interpretation when or if additional information that might affect an interpretation is available. Further, persons aggrieved by an interpretation may appeal to the cognizant ASME Committee or Subcommittee. ASME does not "approve," "certify," "rate," or "endorse" any item, construction, proprietary device, or activity.

Attending Committee Meetings. The PTC Standards Committee regularly holds meetings and/or telephone conferences that are open to the public. Persons wishing to attend any meeting and/or telephone conference should contact the Secretary of the PTC Standards Committee. Future Committee meeting dates and locations can be found on the Committee Page at http://go.asme.org/PTCcommittee.

INTRODUCTION

The distinction between blowers, fans, and compressors in common practice is rather vague; accordingly, machines that use any of these names may be tested under the provisions of this Code provided the gas media is air, pressure of the inlet airflow is close to local atmospheric pressure, and the pressure ratio does not exceed 3.0. The intent of this Code is to provide a means of equalizing a standard for performance testing dynamic blowers (centrifugal blowers) and positive displacement blowers (PD blowers).

The measurement methodology utilized herein for inlet and outlet conditions of the compressed air and the wire-power measurements are for PD and dynamic blowers, except as expressly noted. The driving factor for creating this Performance Test Code is expressed in the title: to provide the methodology for determining required total operating electric power of a packaged blower system. Performance testing is established in a controlled testing environment, with provisions and methodology to establish the highest accuracy and repeatable measurements to extrapolate accurate and repeatable results predicted to site conditions.

This Code provides procedures for testing the performance of wire-to-air blower systems. It also provides methods for converting the resulting performance data from test conditions to alternate inlet and discharge thermodynamic conditions, and identifies the information to be included in the report of test results. The information to be provided in the report includes blower system performance data, the thermodynamic properties of the inlet and discharge process airflow, and the physical configuration and significant components included in the blower system as tested.

The reported data and the procedures defined herein may be used by manufacturers or designers prior to equipment purchase to project performance at inlet air conditions differing from tested or standard conditions.

The reported data and the procedures as defined herein or as modified by agreement between parties may be used to verify performance at specified inlet air conditions differing from the tested conditions.

It is incumbent on the parties conducting the test and using the reported test results to

(a) identify differences between the tested and specified inlet and discharge air conditions

(b) identify differences between tested and proposed or purchased equipment configurations

(c) verify that any variations between test and installed configurations fall within the limits of the methodology for converting performance data to predicted conditions

(d) evaluate the performance impact of differences in configuration or components between the tested blower system and the installed configurations of the blower system

Section 1
Object and Scope

1-1 OBJECT

The purpose of this Code is to measure the electric power consumption associated with a specified performance condition of a blower package referred to as wire-to-air performance.

Blower packages shall include but not be limited to dynamic and rotary positive displacement (PD) types and the ancillary devices required for operational service. This Code determines total input electric power consumption (herein referred to as wire power) and delivery of compressed air from the blower package to the defined system boundary.

1-1.1 Objectives

The objectives of this Code are to

(a) provide the rules for testing blower packages to determine wire-to-air performance using ambient air

(b) provide methods for comparing measured or converted wire-to-air performance to specified performance

(c) account for parasitic losses from mechanical and electrical components as required for a complete operational blower package

1-1.2 Performance Parameters

The principal parameters to be determined in a test are

(a) blower system volumetric flow rate

(b) blower system isentropic head or, alternatively, blower system pressure rise

(c) blower system electric active power (i.e., kilowatt) measured for all power-consuming devices that form the blower system

Henceforth, the term "performance" shall encompass these parameters.

1-1.3 Operating Conditions

Additional quantities that can be determined are

(a) properties of gases at the blower inlet

(b) blower speed

(c) relative set positions of inlet or discharge flow-modulating devices (e.g., valves, vanes, etc.)

Henceforth, the term "operating conditions" shall encompass these conditions.

1-2 SCOPE

The scope of this Code is limited to wire-to-air performance testing of blowers in a controlled environment and does not include field testing. The term "blower" implies that the machine is used primarily for delivery of air at pressure ratios equal to or less than 3.0. This Code does not include procedures for determining the blower system's mechanical and acoustical characteristics, nor is it applicable to machines employing forced interstage cooling.

1-3 APPLICABILITY

A blower test shall be considered an ASME Code test only if the test procedures comply with the procedures and allowed variations specified by this Code.

1-4 TEST UNCERTAINTY

The uncertainties of blower package test results depend on features of the installation and on parameters of the performance test such as the instruments selected, their locations, and the number and frequency of readings. This Code requires an agreement between parties for a pretest and/or a post-test uncertainty analysis. The pretest analysis is required to effectively plan the test. It allows corrective action to be taken prior to the test, either to decrease the uncertainty to a level consistent with the overall objective of the test or to reduce the cost of the test while still attaining the objective. The post-test uncertainty analysis shall be used to determine the uncertainty intervals for the actual test. This analysis should confirm the pretest systematic and random uncertainty estimates. It serves either to validate the quality of the test results or to expose problems.

For a blower package, the following independent items shall be the typical uncertainties when a test is performed in accordance with this Code:

Parameter	Typical Uncertainty
Inlet volumetric flow rate	±1.0% (±1.5%) (refer to subsection 4-5)
Pressure ratio (PD blowers)	±0.5%
Isentropic head (dynamic blowers)	±0.5%
Total wire-power measurement	±0.9%

1-5 REFERENCES

The following publications are referenced in this Code, both in general and in specific sections. For references to specific sections, see the editions of the referenced codes in effect at the time of publication of this Code. The latest edition of codes, if different from those indicated, supersede these editions and should be used for defining testing requirements. In case of discrepancies between this Code and the referenced codes, the latest edition of the referenced codes shall take precedence unless specifically stated otherwise.

ASME B40.100-2013, Pressure Gauges and Gauge Attachments
ASME International Steam Tables for Industrial Use, Third Edition (CRTD-Volume 58), 2014
ASME MFC-3M–2004, Measurement of Fluid Flow in Pipes Using Orifice, Nozzle, and Venturi
ASME PTC 1-2011, General Instructions
ASME PTC 2-2001, Definitions and Values
ASME PTC 9-1970,[1] Displacement Compressors, Vacuum Pumps and Blowers
ASME PTC 10-1997, Performance Test Code on Compressors and Exhausters
ASME PTC 19.1-2013, Test Uncertainty
ASME PTC 19.2-2010, Pressure Measurement
ASME PTC 19.3-1974, Temperature Measurement
ASME PTC 19.3 TW-2010, Thermowells
ASME PTC 19.5-2004, Flow Measurement
Publisher: The American Society of Mechanical Engineers (ASME), Two Park Avenue, New York, NY 10016-5990 (www.asme.org)

[1] This is no longer an American National Standard or an ASME-approved standard. It is available for historical reference only.

Section 2
Definitions and Description of Terms

2-1 SYMBOLS

The symbols used in this Code are as defined in Table 2-1-1 unless otherwise indicated in the text. Both U.S. Customary and SI units are shown. In some cases, other dimensionally consistent units may be used for calculations.

2-2 SUBSCRIPTS

Certain values for thermodynamic state and mass flow rate are used in the computation of the dimensionless performance parameters M_m, Re_m, r_v, η, ϕ, and ψ_s. Unless otherwise specifically stated, the thermodynamic total conditions are used.

The subscripts used in these equations and listed in Table 2-2-2 are interpreted as follows:

(a) The subscript "*i*" on thermodynamic state variables denotes inlet conditions. For single entry streams, it refers to conditions at the section inlet measurement station.

(b) The subscript "*d*" on thermodynamic state variables denotes discharge conditions. It refers to conditions at the mainstream discharge measurement station.

2-3 DEFINITIONS

absolute pressure: the pressure measured above a perfect vacuum.

absolute temperature: the temperature measured above absolute zero. It is stated in degrees Rankine or kelvin. The Rankine temperature is the Fahrenheit temperature plus 459.67 and the Kelvin temperature is the Celsius temperature plus 273.15.

acceptance test: a performance test carried out in accordance with this Code to determine if a new or modified piece of equipment satisfactorily meets its performance criteria, permitting the purchaser to "accept" it from the supplier.

accuracy: the closeness of agreement between a measured value and the true value.

active power: the portion of power that delivers useful work to an electric circuit. Active power, also called real power, is the product of the root mean squared (RMS) voltage (V), RMS current, and power factor (*pf*) times the square-root of the number of phases, i.e., for three-phase power, $P = \sqrt{3} \cdot V \cdot I \cdot pf$, expressed in kilowatts (kW).

ambient pressure: the absolute pressure of the ambient air measured in the vicinity of the blower inlet and measured at the stagnation condition. This will equal barometric pressure under typical conditions.

ambient temperature: the temperature of the ambient air in the vicinity of the blower, but unaffected by it.

apparent power: the vector sum of reactive and real power. It is the square root of the sum of the squares of the active and reactive powers; it is expressed in kilovolt-amperes (kVA).

base reference conditions: the values of all the external parameters, i.e., parameters outside the test boundary to which the test results are corrected.

blower package: defined by the limits of the scope of supply as specified in the overall project contractual agreement pertaining to the blower installation. This shall include all deliverable components to form an operational machine, including but not limited to inlet, discharge, and all power devices that affect power consumption. See also *packaged blower*.

calibration: the process of comparing the response of an instrument to a standard instrument over some measurement range and adjusting the instrument to match the standard if appropriate.

choke flow: the point where a dynamic machine is run at a given speed and the flow is increased until maximum volumetric flow rate is attained and the pressure/volumetric flow rate curve appears nearly vertical. Also called the "stonewall point," further attempts to increase volumetric flow rate result in a negligible change.

compressibility factor: an expression of the deviation of the real gas from an ideal gas. In this Code, the compressibility factor, Z, is defined as 1.0, and omitted from relevant equations.

control volume: a region of space selected for analysis where the flow streams entering and leaving, as well as the power input and heat exchange by conduction, convection, and radiation, can be quantitatively defined. Such a region can be considered to be in equilibrium for both mass and energy balance.

Table 2-1-1 Nomenclature

		Units	
Symbol	Description	U.S. Customary	SI
A	Flow channel cross-sectional area	ft^2	m^2
a	Acoustic velocity	ft/sec	m/s
b	Intercept of empirical correlation	rpm	rpm
C_d	Coefficient of discharge of flow element	dimensionless	dimensionless
c_p	Specific heat at constant pressure	Btu/lbm·°R	J/kg·K
c_v	Specific heat at constant volume	Btu/lbm·°R	J/kg·K
$\overline{c}_p$	Molar specific heat at constant pressure	Btu/lbmol·°R	J/kmol·K
$\overline{c}_v$	Molar specific heat at constant volume	Btu/lbmol·°R	J/kmol·K
D	Diameter	ft	m
d	Diameter of fluid meter bore or individual tubes of tube bundle	ft	m
F	Force	lbf	N
g	Gravitational standard acceleration constant [Note (1)]	32.1741 ft/sec^2	9.8067 m/s^2
g_c	Dimensional constant	32.1741 ft·lbm/lbf·sec^2	1 m·kg/N·s^2
h	Enthalpy	Btu/lbm	J/kg
HR	Humidity ratio	dimensionless	dimensionless
J	Mechanical equivalent of heat	778.169 ft·lbf/Btu	4.187 J/kg·K
k	Flow coefficient for flow conditioning pressure loss	dimensionless	dimensionless
MW	Molecular weight	lbm/lbmol	kg/kmol
M_a	Fluid Mach number	dimensionless	dimensionless
M_m	Machine Mach number	dimensionless	dimensionless
m	Slope of empirical speed correlation	ft^3/revolution	m^3/revolution
N	Rotational speed	rpm	rpm
n	Number, quantity, unit conversion factor	dimensionless	dimensionless
P	Power	hp	kW
p	Pressure (absolute or gauge)	psia (lbf/in.^{2}·abs) psig (lbf/in.^{2}·ga)	kPa (a) kPa (g)
p_v	Velocity pressure	psi (lbf/in.^{2})	kPa
q_m	Mass flow rate	lbm/min	kg/min
q_v	Volumetric flow rate	ft^3/min	m^3/h
$\overline{R}$	Universal gas constant	1,545.3488 ft·lbf/lbmol·°R 1.98588 Btu/lbmol·°R	8314.47 J/kmol·K
$R_g = R_{mix}$	Specific gas constant for the mixture ($\overline{R}/MW_{mix}$)	ft·lbf/lbm·°R Btu/lbm·°R	J/kg·K
RA, RB, RC	Machine Reynolds number correction constants	dimensionless	dimensionless
Re	Fluid Reynolds number	dimensionless	dimensionless
Re_m	Machine Reynolds number	dimensionless	dimensionless
RH	Relative humidity	%	%
r	Pressure ratio across fluid meter	dimensionless	dimensionless
r_f	Recovery factor	dimensionless	dimensionless
r_p	Pressure ratio	dimensionless	dimensionless
r_s	Gas power ratio	dimensionless	dimensionless
r_v	Ratio of specific volumes	dimensionless	dimensionless
T	Temperature	°R, °F	K, °C
t	Time	sec	s
u	Internal energy	Btu/lbm	J/kg
U	Blade tip speed	ft/sec	m/s
V	Velocity	ft/sec	m/s

Table 2-1-1 Nomenclature (Cont'd)

		Units	
Symbol	**Description**	**U.S. Customary**	**SI**
v	Specific volume	ft^3/lbm	m^3/kg
W	Work per unit mass	ft·lbf/lbm	J/kg
x	Mole fraction	dimensionless	dimensionless
α_p	Coefficient of thermal expansion of a material	in./in.·°F	m/m·°C
β	Diameter ratio of fluid meter, d/D	dimensionless	dimensionless
β_{sv}	Temperature coefficient for saturated vapor pressure, empirical	dimensionless	dimensionless
Δp	Differential pressure	psi (lbf/in.^{2})	kPa
ε	Surface roughness	in.	mm
ε_1	Gas expansion factor	dimensionless	dimensionless
η	Efficiency	dimensionless	dimensionless
ϕ	Flow coefficient	dimensionless	dimensionless
κ	Ratio of specific heats, c_p/c_v	dimensionless	dimensionless
μ	Absolute viscosity	lbm/ft·sec	N·s/m^2
ν	Kinematic viscosity	ft^2/sec	m^2/s
ρ	Density	lbm/ft^3	kg/m^3
ψ_s	Isentropic compression work per unit mass coefficient (isentropic head coefficient)	dimensionless	dimensionless
∂	Partial derivative	dimensionless	dimensionless

NOTE: (1) For local acceleration, refer to ASME PTC 2-2001.

current transducer (CT) system: an instrument transformer used to reduce a high current to a proportionately lower current that may be safely applied to a measuring instrument.

data acquisition system (DAQ): a system, typically microprocessor based, that accepts electric signals representative of measured physical parameters from transducers or transmitters. DAQ may include all or some of the following functions:

(a) conversion to engineering units
(b) data display
(c) archiving and data storage
(d) analog and digital conversion
(e) calculation of secondary data from measurements

differential pressure: the difference between any two pressures measured with respect to a common reference (e.g., the difference between two absolute pressures).

dimensional constant: the dimensional constant, g_c, is required to account for the units of length, time, and force. It is equal to 32.1741 ft·lbm/lbf·sec^2. The numerical value is unaffected by the local gravitational acceleration.

dimensionless analysis: the algebraic theory of equations that are invariant under arbitrary transformations of the size of the fundamental units of measurement; utilizing dimensionally homogeneous equations to derive dimensionless products for particular systems of measurement, to reduce a relationship to a complete set of dimensionless products.

discharge static pressure: the absolute static pressure that exists at the discharge control volume.

discharge static temperature: the absolute static temperature that exists at the discharge control volume.

discharge total pressure: the absolute total pressure that exists at the discharge control volume. Unless specifically stated otherwise, this is the blower discharge pressure as used in this Code.

discharge total temperature: the absolute total temperature that exists at the discharge control volume. Unless specifically stated otherwise, this is the blower discharge temperature as used in this Code.

dynamic (centrifugal) blower: a machine that creates airflow and static pressure rise by means of a rotating impeller transferring kinetic energy to an airstream and then converts some of that energy to static pressure.

equivalence: the specified operating conditions and the test operating conditions which, for the purpose of this Code, are said to demonstrate equivalence when, for the same flow coefficient, the ratios of the two dimensionless parameters (specific volume ratio and machine Mach number) fall within the limits prescribed in Tables 3-5.4-1 and 3-5.4-2 and Figure 3-5.4-1.

Table 2-2-2 Subscripts

Symbol	Description
1, 1n	Upstream of fluid meter
2, 2n	Downstream or at throat of fluid meter, at impeller outlet blade tip diameter
a	Ambient
abs	Absolute
adj	Adjusted
av	Average
d	Blower discharge conditions at test reference boundary
da	Dry air
db	Dry-bulb
des	Design
est	Estimated
exp	Reference for thermal expansion ratio
ga	Gauge
i	Blower inlet conditions at test reference boundary
mix	Gas mixture
meas	Measured
N	Total number of readings
p	Polytropic process
pr	Predicted
s	Isentropic process
sh	Shaft
sp	Specified conditions
static	Static
std	Standard conditions
sv	Saturated vapor
t	Test conditions
tot	Total conditions
vp	Vapor

external cooling: the medium supplied to the blower to which the generated heat is finally rejected. This Code applies to a compression apparatus that does not contain compressed gas cooling, or compression jacket cooling by liquid means, or a form of intercooling other than free convection (non-forced). See also *intercooling*.

flow coefficient: a dimensionless parameter defined as the inlet volumetric flow rate divided by the product of the impeller rotational tip speed and the impeller outer diametric area.

fluctuation: the highest reading minus the lowest reading divided by the average of all readings for a specific measurement, expressed as a percent.

fluid Reynolds number: the Reynolds number (Re) for the gas flow in a pipe. It is defined by the equation

$$\mathrm{Re} = VD/\nu$$

where

D = characteristic length of inside pipe diameter at the pressure control volume

V = average velocity at the pressure control volume

ν = kinematic viscosity that exists for the static temperature and pressure at the control volume

The variables in the Reynolds number must be expressed in consistent units to yield a dimensionless ratio. In the case of velocity, *V,* at the pressure control volume, the local velocity may be calculated from the local conditions of mass flow rate; inside pipe diameter, *D*, and resulting density, ρ, of the local temperature and pressure; and molecular weight, MW.

full scale: the full-scale measurement range of a measuring instrument utilized in the evaluation of instrument resolution for suitability and measurement quality or uncertainty.

gauge pressure: pressure that is measured directly with the existing barometric pressure as the zero base reference.

inlet static pressure: the absolute static pressure that exists at the inlet to the control volume.

inlet static temperature: the absolute static temperature that exists at the inlet to the control volume.

inlet total pressure: the absolute total pressure that exists at the inlet to the control volume. Unless specifically stated otherwise, this is the blower inlet pressure as used in this Code.

inlet total temperature: the absolute total temperature that exists at the inlet to the control volume. Unless specifically stated otherwise, this is the blower inlet temperature used in this Code.

inlet volumetric flow rate: the rate of flow that is determined by delivered mass flow rate divided by inlet total density as defined by the inlet to the control volume boundary.

instrument: a tool or device used to measure physical dimensions of length, thickness, width, weight, or any other value of a variable. These variables can include size, weight, pressure, temperature, fluid flow, voltage, electric current, density, viscosity, and power. Sensors are included that may not, by themselves, incorporate a display but may transmit signals to remote computer-type devices for display, processing, or process control. Also included are items of ancillary equipment directly affecting the display of the primary instrument, e.g., ammeter shunt.

intercooling: the removal of heat from a gas between stages. This Code applies to a compression apparatus that does not contain compressed gas cooling, or compression jacket cooling by liquid means, or a form of intercooling other than free convection (non-forced). See also *external cooling*.

isentropic compression: a reversible, adiabatic compression process where entropy remains constant. Unless specifically stated, isentropic compression is considered in this Code.

isentropic enthalpy rise: also called isentropic head; it is the energy required to isentropically compress a unit mass of gas from the inlet total pressure and total temperature to the discharge total pressure. The total pressure and temperature are used to account for the compression of the gas and the change in the kinetic energy of the gas. The change in the gravitational potential energy of the gas is assumed negligible between inlet and outlet process connections. Isentropic head is considered in this Code.

isentropic head coefficient: the dimensionless ratio of the isentropic head to the sum of the squares of the blade tip speeds of all stages in a given section.

isentropic power of compression: the ideal power of compression for a given isentropic enthalpy rise for a given mass flow rate.

machine Mach number: defined as the ratio of the blade velocity at the largest blade tip diameter of the first impeller for dynamic machines to the acoustic velocity at the total inlet condition.

NOTE: This is not the local fluid Mach number.

machine Reynolds number: defined by the equation

$$\mathrm{Re}_m = Ub/\nu$$

where

b = a characteristic length

U = velocity at the outer blade tip diameter of the first impeller or of the first stage rotor tip diameter of the leading edge

ν = total kinematic viscosity of the gas at the blower inlet

For dynamic blowers, b shall be taken as the outlet width at the outer blade diameter of the first stage impeller. These variables must be expressed in consistent units to yield a dimensionless ratio.

measurement error: the true, unknown difference between the measured value and the true value.

measurement uncertainty: the uncertainty of a measured result, based on a combination of the systematic and precision statistical error components of uncertainty, that yields a band of confidence about the true value.

mechanical losses: the total power consumed by frictional losses of integral gearing, bearings, and seals, etc.

normal inlet volumetric flow rate: see *standard inlet volumetric flow rate*.

packaged blower: a blower with prime mover and transmission that is fully piped and wired internally, includes ancillary and auxiliary items of equipment, and may be stationary or mobile (portable unit), where these are within the scope of supply. See also *blower package*.

parties to a test: those persons and companies interested in the results. May include, but shall not be limited to, blower manufacturer, end user or equipment owner, consulting engineers, installation contractors, blower packager, or designee(s) of the above.

polytropic compression: a reversible compression process between the inlet total pressure and temperature and the discharge total pressure and temperature. The total pressures and temperatures are used to account for the compression of the gas and the change in the kinetic energy of the gas. The change in the gravitational potential energy is assumed negligible between inlet and outlet process connections. The polytropic process follows a path such that the polytropic exponent is constant during the compression process.

positive displacement (PD) blower: a machine that creates airflow and static pressure rise by allowing successive volumes of gas to be aspirated into and exhausted out of a closed space by means of the displacement of a compression element.

potential transformer (pt): an instrument transformer used to reduce a high electric voltage to a proportionately lower electric voltage that may be safely applied to a measuring instrument to measure electric potential.

power factor (pf): the cosine of the angle of phase shift between voltage and current in an inductive load.

pressure ratio: the ratio of the absolute discharge total pressure to the absolute inlet total pressure.

pressure rise: the difference between the discharge total pressure and the inlet total pressure.

raw data: the recorded observation of an instrument taken during the test run.

reactive power: power stored in and discharged by inductive loads in a circuit. It is expressed in kilovolt-amperes reactive (kvar). Reactive components cause a phase shift between voltage and current in an AC circuit.

reading: the average of the corrected individual observations (raw data) at any given measurement station.

shaft rotational speed: the revolutions of the motor or blower drive shaft per unit of time.

similitude: similarity of behavior for modeling systems with equal similarity parameters sharing geometric similarity, kinematic similarity, and dynamic similarity. This concept provides a method of comparison between fundamentally similar physical systems by following an appropriate matching of the dimensionless parameters. For the purpose of this definition, similitude and similarity are used interchangeably.

specific volume: the volume occupied by a unit mass of gas. This is a thermodynamic parameter determined once the total pressure and temperature are known. The specific volume is the reciprocal of the density.

specified operating conditions: those conditions for which the blower performance is to be determined.

stage: comprised, for a dynamic blower, of a single impeller and its associated stationary flow passages.

standard inlet volumetric flow rate: often defined by industry with a number of different conditions that may be industry- or user-specific, defining a standard cubic feet per minute (SCFM) or "normal," N, cubic meters per hour, $N{\cdot}m^3/h$. An example of this can be seen as SCFM defined by a gas condition of 68°F, 14.7 psia, and 36% RH. Alternatively, this may be defined in $N{\cdot}m^3/h$ as a gas condition in SI units of 0°C, 101.3259 kPa, and 0% RH. The gas conditions defining S or N may be different than the values above, but must be identified for the conversions herein. Refer to Section 3 for additional guidance. Essentially, the standard condition flow values above are a mass flow; hence the importance of gathering the defining gas condition.

static pressure: the absolute or gauge pressure determined in such a way that no effect is produced by the velocity of a flowing fluid.

static temperature: the temperature determined in such a way that no effect is produced by the velocity of a flowing fluid.

steady state: the condition in which change in temperature rise $(T_d - T_i)$ within a 5-min interval is less than 1°F (0.55°C).

surge point: defined in dynamic blowers as the inlet volumetric flow rate for a given speed below which the blower operation becomes unstable. This occurs when flow is reduced and the blower back pressure exceeds the pressure developed by the blower; a breakdown in flow results. This immediately causes a reversal in the flow direction and reduces the blower back pressure. The moment this happens, regular compression is resumed and the cycle is repeated.

systematic error: a consistent error caused by an inaccuracy involving either the observation or measurement process inherent to the system. Systematic errors are not random or caused by chance.

temperature rise: the difference between the discharge total temperature and the inlet total temperature.

test operating conditions: the operating conditions prevailing during the test.

test point: three or more test readings that fall within the permissible specified fluctuation and are averaged.

test reading: one recording of all required test instrumentation.

test tolerance: a commercially agreed upon tolerance that may be applied to test results or to guarantees. Tolerance is often related to variability in the performance of machines of the same design. Although not advised by ASME (see Notice), parties may agree to include a component of test tolerance related to test uncertainty. This may or may not have some relationship to measurement uncertainty. Test tolerances are purely contractual issues and thus totally out of the jurisdiction of ASME Performance Test Codes.

total pressure: also called stagnation pressure; it is the absolute or gauge pressure that exists when a moving fluid is brought to rest and its kinetic energy is converted to an enthalpy rise by an isentropic process from the flow condition to the stagnation condition. In a stationary body of fluid, the static and total pressures are equal.

total temperature: also called stagnation temperature; it is the temperature that exists when a moving fluid is brought to rest and its kinetic energy is converted to an enthalpy rise by an isentropic process from the flow condition to the stagnation condition. In a stationary body of fluid, the static and the total temperatures are equal.

traceable: the availability of records demonstrating an instrument can be traced through a series of calibrations to an appropriate, recognized national or international standard.

turndown: the ratio of the minimum stated volumetric flow rate and the maximum stated volumetric flow rate at the specified inlet conditions. This can alternately be expressed as a difference.

uncertainty: the interval about the measurement or result that contains the true value for a given confidence level. Expressed in ±U, it may be used as a quantitative assessment of the quality of a test, and a threshold value may be used by agreement between parties as a standard for a test. While not advised by ASME (see Notice), it may be used in an agreement between parties to form an acceptance interval around a test result for comparison of that result to specified performance. Without an agreement between parties, uncertainty shall not be used as a component of test tolerance.

variable voltage/variable frequency (V.V.V.F): an electronic device used to convert AC line frequency to a recreated variable output of voltage or current at variable frequency to drive an electro-mechanical motor with varying speed and varying torque capability. This is noted as variable frequency drive (VFD) herein.

variable frequency drive (VFD): see *variable voltage/variable frequency*.

velocity pressure: also called kinetic pressure; it is the difference between the total pressure and the static pressure at the same point in a fluid.

velocity temperature: also called kinetic temperature; it is the difference between the total temperature and the static temperature at the control volume.

wire-to-air power: the blower package total wire power, or the electric power measured at the power input to the blower package. This shall include all power-consuming electrical components of the blower package as required for installation and normal operation, i.e., drive motor, motor cooling fan, magnetic bearing and controller, bearing cooling fans, coolant pump and heat exchanger, enclosure and package cooling fan, sine wave filter or output reactor, variable frequency drive and cooling fan, input choke or line reactor, harmonic filter, local control panel, programmable logic controller (PLC) or processor, human machine interface (HMI) and miscellaneous electronics, voltage transformer(s), DC power supplies, power conditioner, etc. as identified by agreement between the parties. If the blower package receives multiple power feeds, this is the sum of all wire powers measured individually.

Section 3
Guiding Principles

3-1 INTRODUCTION

Application of this Code to a specific blower system test requires various decisions. This Section explains what decisions shall be made and gives general guidelines for performing a Code test.

Any test shall be performed only after the blower system has been found by inspection to be in a satisfactory condition to undergo the test.

3-2 PERFORMANCE TEST OPERATING PHILOSOPHY

The purpose of this Code is to measure the electric power consumption associated with a specified performance condition of a blower package, referred to as wire-to-air performance.

This Code describes procedures for coincident measurements of blower package air capacity (as defined in terms of inlet volumetric flow rate), isentropic head or blower pressure (PD blowers), and electric input active power (input wire). These measurements are conducted to determine performance verification with a specified inlet volumetric flow rate at a specified inlet location and isentropic head or blower pressure (PD blowers) condition. A specified performance condition is comprised of inlet volumetric flow rate, discharge pressure requirement, barometric pressure, inlet pressure (optionally adjusted for additional inlet loss considerations, e.g., dirty filter loss), inlet temperature, and inlet moisture content (relative humidity). Performance verification shows that a blower package can produce the specified performance condition and the input electric power required to operate the blower package.

Recognizing that the blower inlet condition in a test facility can almost never be matched to the specified condition, this Code provides a basis for deriving a test operating condition that most closely matches a specified operating condition with priority emphasis on matching inlet volumetric flow rate and parameters for isentropic head or pressure ratio.

While blower work and other thermodynamic properties at test and specified conditions may be more similar at speeds other than the speed required for the specified condition, the contributions of noncompression components to the overall electric power consumption of the package may be poorly represented at alternative operating speeds, e.g., mechanical considerations. This Code provides guidance on permissible deviations both for operating conditions and for the thermodynamic properties of air.

For dynamic blowers, the operating speed at the specified point is achieved via the matching of inlet volumetric flow rate and isentropic head at test conditions. For PD blowers, the operating speed at the specified point is achieved via the matching of inlet volumetric flow rate and pressure ratio at test conditions. The matching of inlet volumetric flow rate and isentropic head (dynamic blowers) or pressure ratio (PD blowers) shall be considered herein as the primary method of testing.

Users of this Code are reminded to properly differentiate blower inlet volumetric flow rate defined herein from the popular forms of standard or normal inlet volumetric flow rate (e.g., SCFM or $N \cdot m^3/h$) in blower performance specifications. Standard or normal inlet volumetric flow rate indicates an inlet volumetric flow rate at one distinct set of standard or normal inlet conditions identifying temperature, barometric pressure, and inlet moisture content that are not related to the inlet conditions in which the blower is specified to perform. Standard or normal inlet volumetric flow rate is, in essence, a means of stating that a blower is required to deliver a specific dry air mass flow rate. When presented with specified blower performance conditions that use standard or normal inlet volumetric flow rate requirements, users of this Code should immediately determine the mass flow of dry air associated with the specified standard or normal inlet volumetric flow rate and convert that mass flow to a volumetric moist air inlet volumetric flow rate required to convey that same mass flow of dry air at the specified inlet conditions. The inlet volumetric flow rate determined in this manner will be the appropriate inlet volumetric flow rate used with evaluations made in accordance with this Code.

The general approach for finding a test performance condition is to match the inlet volumetric flow rate of the blower at test condition to the inlet volumetric flow rate at the specified condition. For a dynamic blower, the pressure rise for the test condition is found by determining the isentropic head at the specified condition and then calculating the pressure rise necessary to achieve the same isentropic head at the test condition.

For a PD blower, the pressure rise for the test condition is found by determining the pressure ratio at the specified condition and then achieving the same pressure ratio at the test condition.

Achieving the test performance described here will result in a mass flow rate and associated power input that does not match the specified condition directly. For dynamic and PD blowers, the power at the specified condition is determined by translating the power measured at the test condition as defined herein to the specified condition. For these volumetric machines, the translation of input electric power measurement considers the ratio of inlet air density at test and specified conditions to compare the ratio of the delivered mass flow rates for the test and specified conditions, and minor deviations in the matching of inlet volumetric flow rate, isentropic head (dynamic blower), or pressure ratio (PD blower), as appropriately defined for the type of blower package. Matching inlet volumetric flow rate and isentropic head (dynamic blower) or inlet volumetric flow rate and pressure ratio (PD blower), and translating the input electric power using this method, will accurately establish the operating performance at specified conditions. Additional items specified in the control boundary that may deviate from the thermodynamic and electric reference boundary at test are quantified in Tables 3-5.2-1 and 3-5.2-2.

Electric input power addressed in this Code refers specifically to active or real electric power, P, and not to apparent power (which includes the reactive component of supplied power). While blower systems do utilize some reactive power, this Code considers that most users are directly charged for electric power primarily based on active power consumed at a site. Charges for reactive power are often captured in site-specific surcharges, and it is considered impractical to attempt to quantify the impact of a specific blower system on the reactive power component of the power costs. Active power is used in predicting power at specified conditions based on active power measured at test conditions.

NOTE: As described in the Notice, when tests are run in accordance with a Code, the test results themselves, without adjustment for uncertainty, yield the best available indication of the actual performance of the tested equipment. ASME Performance Test Codes do not specify means to compare those results to contractual guarantees. Therefore, it is recommended that the parties to a commercial test agree before starting the test and preferably before signing the contract on the method to be used for comparing the test results to the contractual guarantees. It is beyond the scope of any Code to determine or interpret how such comparisons shall be made.

3-2.1 Prior Agreements

The typical items upon which agreement shall be reached prior to conducting the test, as documented in a formal test plan, include

(a) detailed test objectives, including specified performance and operating conditions to be tested
(b) location and timing of test
(c) individual designated as responsible for conducting the test
(d) test personnel and assignments, including witnesses
(e) test boundaries (thermodynamic and electric reference boundaries)
(f) schematic and graphic description of measurement locations (test apparatus layout)
(g) selection of type of instruments
(h) method and timing of calibration of instruments
(i) confidentiality of test results
(j) number of copies of original data required
(k) data to be recorded and method of recording and archiving data
(l) values of measurement uncertainty and method of determining overall test uncertainty
(m) method of operating equipment under test, including that of any auxiliary equipment, the performance of which may influence the test result
(n) method of maintaining constant operating conditions as near as possible to those specified
(o) method of determining duration of operation under test conditions before test readings are started
(p) duration and number of test runs
(q) number and frequency of observations
(r) method of computing results including method of translation of test conditions to the specified condition (including whether or not the effects of machine Reynolds number correction, leakage flow, or mechanical losses are to be considered)
(s) method of comparing test results with specified performance
(t) establishment of whether or not test tolerance(s) will be used in comparing test results, adjusted to specified conditions, with specified performance
(u) test report format
(v) pretest inspections
(w) establishment of threshold values for pretest uncertainty and/or post-test uncertainty intervals for acceptance of test quality
(x) intent of contract or specification test requirements, if ambiguities or omissions appear evident

3-2.2 Preliminary Test Runs

Preliminary test runs, with records, are recommended to determine if equipment is in proper condition for testing, to serve to check instruments and methods of measurement, to check adequacy of organization and procedures, and to train personnel. All parties to the test may conduct reasonable preliminary test runs as necessary. Observations during preliminary test runs should be carried through to the calculation of results as an overall check of procedure, layout, and organization. If such a preliminary test run complies with all the necessary requirements of the appropriate test code, it may be used as an official test run within the meaning of the applicable code. This also functions to ascertain if the reading fluctuations fall within the limits prescribed in Table 3-5.5-1.

All instrument observations pertinent to the test shall be taken during the preliminary test run. These commonly include

(a) inlet pressure
(b) inlet temperature
(c) relative humidity or wet bulb temperature
(d) discharge pressure
(e) discharge temperature
(f) electric input power consumption
(g) flow device pressures and temperatures
(h) speed
(i) lubricant temperatures, inlet and outlet, of bearings, seals, and speed changing gear, if applicable
(j) coolant and lubricant flows, if applicable
(k) barometric pressure
(l) belt tension
(m) time

A set of sample calculations shall be made using the preliminary test data to assure that the correct test speed has been selected, and that the test parameters of Table 3-5.4-1 or Table 3-5.4-2 are obtainable for the overall performance run.

3-3 TESTS: SPECIAL CONSIDERATIONS OF THIS TEST CODE

3-3.1 Conversion of Test Results

The methods of this Code may be applied for conversion of test results to specified operating conditions for blower packages.

3-3.2 Application Limitations

This Code shall not apply to blower packages with intercoolers. Parties may refer to ASME PTC 10 for such applications.

3-3.3 Side Streams

This code shall not apply to blowers with side streams. Side streams consider the capacity inflow or outflow of a blower section that crosses the thermodynamic reference and thus adds to or subtracts from the delivered process gas and thus provides a deviation in the measurement quantities between test and site conditions.

3-3.4 Inlet Volumetric Flow Rate

Inlet volumetric flow rate shall be measured at the discharge of the blower package to ensure leakage flow is not included in the delivered air measurement. Inlet volumetric flow rate is defined as the delivered mass flow divided by the blower package inlet density. The blower package inlet density may be equal to ambient density, or different from ambient density as a consequence of connected installation piping and the associated pressure losses.

3-3.5 Specific Volume Ratio

Matching the specific volume ratio between test and specified conditions shall be a primary objective of this Test Code. The allowable deviations detailed herein ensure the consideration of similarity and acceptability for comparing between test and specified conditions.

3-3.6 Exchanges of Heat Across the Control Volume

This Code includes testing of blowers where there may be incidental exchanges of heat across the control volume that are not directly related to the work of the blower. Examples include active rejection of heat from motors, VFDs, power conditioning appurtenances, and/or control components. The components being cooled may be within the electric power control volume as may be the components that provide the active heat rejection.

Incidental heat rejection systems may transfer heat to an independent external environment where the rejected heat has no further effect on the blower system. In this case, the parties should be mutually aware of this heat load and its effect, if any, on the independent external environment.

It is important for the parties to recognize and agree upon the magnitude of incidental heat exchanges across the blower system control volume; however, this Code does not address measuring these loads or testing for conformance with specifications. The parties may agree to make such measurements with methods appropriate to the manner and medium(s) of heat exchange.

Incidental heat rejection systems may also transfer heat to the inlet gas flow of the blower within the control volume of the blower system. For these systems, the blower work is calculated based upon conditions external to the thermodynamic reference boundary for the package and the control volume. Variations of the magnitude of the internal heat transfer between test and specified conditions are not considered in this Test Code.

The overall isentropic head or pressure ratio following the relevant compression technology, inlet volumetric flow rate, and package wire power shall not be affected between test and specified conditions, taking thermodynamic and electric system reference boundaries into consideration.

3-3.7 Measurement of Speed

This Code focuses on inlet volumetric air flow, electric power consumption, and pressure ratio as the primary testing parameters. Speed is not included as part of the preferred calculation methodology for determining wire-to-air power or for correcting measurements at test conditions to projected performance at specified conditions. The Code requirements are compatible with constant-speed blower systems and systems employing alternate methods of flow modulation.

Speed may be used in secondary calculations such as Re_m (see Nonmandatory Appendix D). Blower system limitations or test ambient conditions may prevent achieving the required volumetric flow rate. In these cases, procedures are provided in the Code for flow corrections based on blower speed at test conditions. The procedure for flow correction for dynamic blowers is provided in para. 3-5.4.1. The procedure for flow correction for PD blowers is provided in para. 5-4.5.1.

Speed may, by agreement of the parties, be included in the test measurements and test reports. In some cases speed is useful as reference information or as confirmation of compliance with specified requirements and limits.

In all cases where speed measurement is required, it shall conform to subsection 4-7. The requirement for speed measurement, measurement techniques, allowable deviations, and allowable fluctuations shall be agreed to by the parties prior to conducting the test.

3-3.8 Mechanical Flow Modulation

Dynamic blowers may be modulated by throttling devices on inlet or discharge, or by means of guide vanes on inlet or discharge.

If blower air flow is modulated by inlet throttling valves or by inlet guide vanes, the devices shall be considered inside the thermodynamic reference boundary provided in para. 3-5.2. All measurements for test conditions shall be made upstream of these devices.

If blower air flow is modulated by discharge throttling valves or discharge guide vanes, the devices shall be considered inside the thermodynamic reference boundary provided in para. 3-5.2. All measurements for test conditions shall be made downstream of these devices. A second discharge throttling valve downstream of the pressure measurement point is used to simulate system back pressure, and is not part of the reference boundary.

For all guide vanes and throttling valves, percentage open values shall be recorded as reference for each data point. Percentage open values shall be based on the angular or linear travel of the operator as limited by the mechanical limits of the operator. Limit switches or other electrical limits on operator movement that differ from the mechanical limitations shall be ignored.

3-3.9 Preparation

Prior to conducting a test, the manufacturer or supplier shall have reasonable opportunity to examine the equipment, correct defects, and render the equipment suitable to test. The manufacturer, however, is not thereby empowered to alter or adjust equipment or conditions in such a way that regulations, contract, safety, or other stipulations are altered or voided. The manufacturer may not make adjustments to the equipment for test purposes that may prevent immediate, continuous, and reliable operation at all capacities or outputs under all specified operating conditions. Any actions taken must be documented and immediately reported to all parties to the test. As an example, belt tension shall be within the belt manufacturer's published recommendations; it is appropriate for manufacturer or supplier to check and readjust belt tension after machine has run for a break-in period that has been identified and completed as required.

3-3.10 Starting and Stopping

Tests shall be conducted as promptly as possible following initial equipment operation and preliminary test runs. The equipment should be operated for sufficient time to demonstrate that intended test conditions have been established, i.e., steady state. Agreement on procedures and time should be reached before commencing the test.

3-3.11 Steady State

The blower shall be operated at the required conditions for a sufficient period of time to show that all variables have stabilized and achieved a steady-state condition. Steady state is defined as demonstrating the difference between inlet and outlet temperatures of the blower package [$\Delta T = (T_d - T_i)$] does not vary greater than 1°F (0.55°C) for a period of 5 min or more.

3-3.12 Readjustments

During the test, readjustments to the equipment that can influence the results of the test shall require repetition of any test runs conducted prior to the readjustments. There shall be no adjustments that are inappropriate for reliable and continuous operation following a test under any and all of the specified outputs and operating conditions. For example, belt tension may require readjustment to maintain manufacturer's recommended specification. If any such readjustment is required, all affected test runs should be discarded and all suspect tests rerun, including as a minimum the test run immediately prior to the readjustment.

3-3.13 Data Collection

Data shall be collected manually or by automatic data collecting equipment. If data is collected manually, a suitable number of observers shall be employed to insure suffiecient time to take and record all readings with appropriate care and precision. Automatic data logging and advanced instrument systems shall be calibrated to the required accuracy. If necessary, specify duplicate instrumentation and take simultaneous readings for certain test points to attain the specified accuracy of the test.

Data acquisition systems (DAQ), including input and output devices and communications, shall be installed to minimize signal noise from electromagnetic and radio interference. Algorithms used for conversion of signals to engineering units and for calculation of secondary data and performance values shall be documented. The accuracy of conversions and calculations shall be demonstrated by at least one set of data calculations showing the complete algebraic sequence of values. Data displayed in the report of results shall use a number of significant digits consistent with the uncertainty of the test.

3-3.14 Test Administration

The parties to the test shall designate a test coordinator to direct the test. Communication arrangements between all test parties and personnel and the test coordinator should be established. Complete written records of the test, including even those details that at the time may seem irrelevant, should be prepared. Controls by ordinary operating (indicating, reporting, or integrating) instruments, the preparation of graphic logs, and close supervision should be established to assure the equipment under test is operating in substantial accord with the intended conditions.

3-4 INSTRUMENTS

3-4.1 Location and Identification of Instruments

Transducers shall be located to minimize the effect of ambient conditions on uncertainty, e.g., temperature or temperature variations. Care shall be used in routing lead wires to the data collection equipment via shielded cabling to prevent electric noise in the signal. Manual instruments shall be located so that they can be read with precision and convenience by the observer(s). All instruments shall be marked uniquely and unmistakably for identification. Calibration tables, charts, or mathematical relationships shall be readily available to all parties of the test. Observers recording data shall be instructed on the desired degree of precision of readings. Test instruments shall be arranged, installed, and calibrated as per Section 4.

3-4.2 Frequency and Timing of Observations

The timing of instrument observations shall be determined by an analysis of the time lag of both the instrument and the process so that a correct and meaningful mean value and departure from allowable operating conditions shall be determined. Sufficient observations shall be recorded to prove that steady-state conditions existed during the test where this is a requirement. A sufficient number of observations shall be taken to reduce the random component of uncertainty to an acceptable level.

3-5 TEST OPERATION

3-5.1 Safety

The party providing the test site shall be responsible for establishing the requirements of system protection. An overall comprehensive hazard and safety plan is advised. An emergency exit and evacuation plan should be considered.

3-5.2 Reference Boundaries

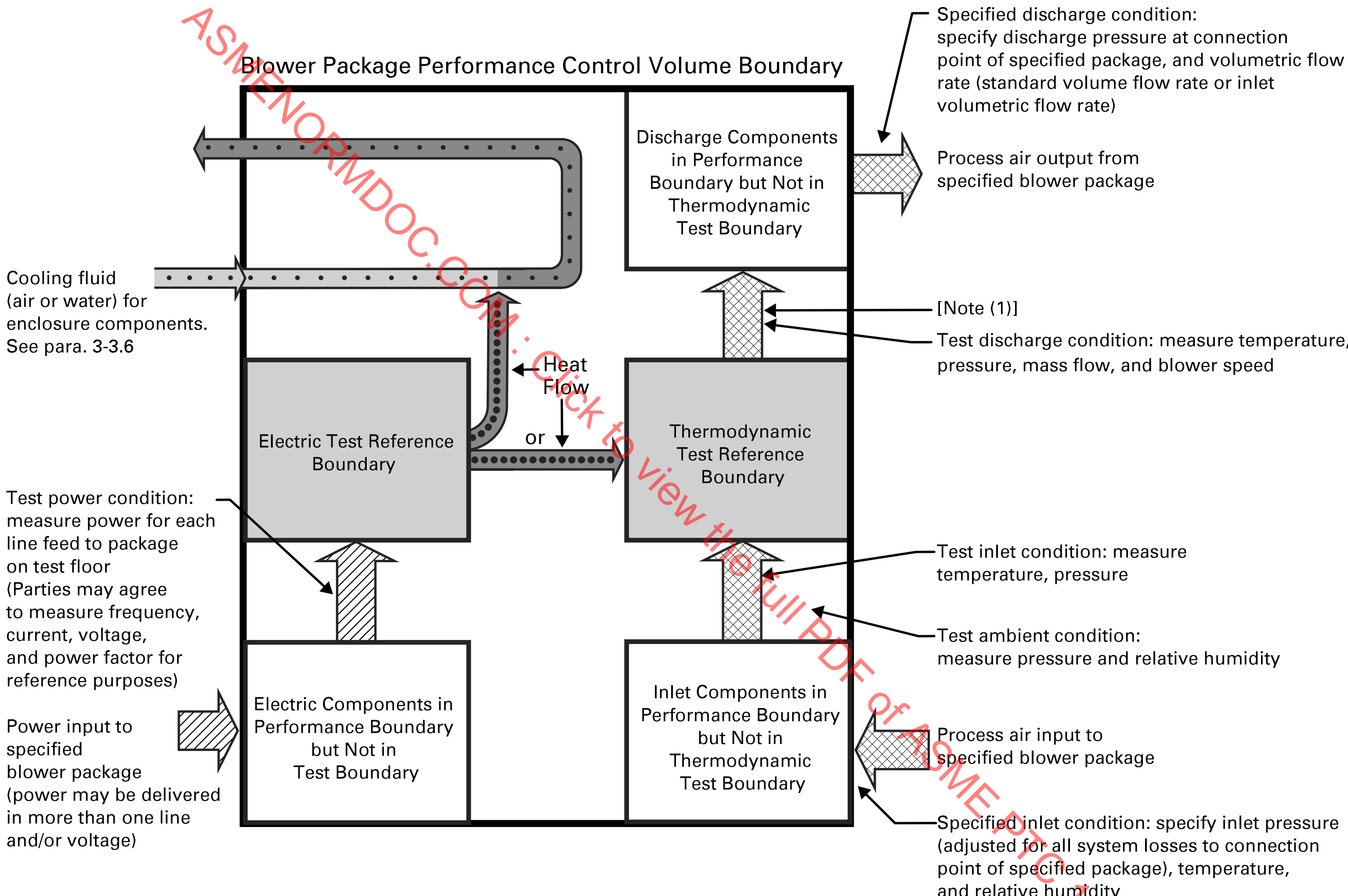
Figure 3-5.2-1 depicts a generic performance boundary of a blower system. Within this performance boundary, there are two reference boundaries: a thermodynamic performance boundary and an electric performance boundary.

(a) Thermodynamic Performance Boundary. The thermodynamic performance boundary defined herein shall be specified as the plane of the inlet airstream into the blower package, referenced as subscript "*i*"; the package perimeter wetted by the process fluid; and the plane of the outlet process connection, referenced as subscript "*d*." The ambient conditions, referenced as subscript "*a*," shall represent fluid properties measured prior to passing the inlet plane at locations defined per paras. 4-3.12 and 4-4.8. The thermodynamic performance boundary includes components within the test boundary and outside the test boundary. Table 3-5.2-1 is intended to be used as a test-specific checklist to define components that shall be included or excluded from the performance boundary and agreed upon between the parties to a test.

The package test shall include all thermodynamic-affecting devices, measured collectively or separately, identified and considered in the package pressure (isentropic head) calculation. Individual thermodynamic affecting devices shall be agreed to and noted in the test report defined in Section 6. It is the responsibility of the specifier to identify differences between ambient conditions and conditions of the process air input to the blower package as shown in Figure 3-5.2-1.

(b) Electric Performance Boundary. The electric system performance boundary defined herein shall be specified to include all electrical components of the blower package, as defined by the contractual scope of supply, to form the site operational package. Table 3-5.2-2 is intended to be used

Figure 3-5.2-1 Blower Package Performance Boundary and Internal Reference Boundaries



NOTE:
(1) Test discharge operating condition: set blower condition to match inlet volumetric flow at specified condition for setting pressures.
(a) Determine, by calculation, specified inlet pressure to account for inlet components not in test boundary.
(b) Determine, by calculation, specified discharge pressure to account for discharge components not in test boundary.
(c) Set pressure to match specified isentropic head (centrifugal) or to match specified pressure ratio (displacement).

See Section 3-2.

Table 3-5.2-1 Process and Fluid Components

Component	Included in Performance Boundary: Included in Test	Determine by Calculation	Not Applicable
Inlet filter			
Inlet silencer			
Discharge silencer			
Inlet isolation valve			
Throttling valve			
After cooler			
Misc. pipe and fittings			
Inlet air cooler			
Discharge check valve			
Discharge isolation valve			
Enclosure doors or panel openings			
Estimated system inlet press drop			
Additional components not listed included as forming the blower package			

Table 3-5.2-2 Electric Power-Related Components

Component	Included in Performance Boundary: Included in Test	Determine by Calculation	Not Applicable
Drive motor			
Motor cooling fan(s)			
Magnetic bearing and controller			
Bearing cooling fan(s)			
Coolant pumps			
Lubrication pumps and accessories			
Heat exchanger fans			
Package cooling fan			
VFD			
VFD line-side power-conditioning equipment			
VFD load-side power-conditioning equipment			
Eddy current or variable speed clutch			
Operation control panel(s)			
Power/isolation transformers and power supplies			
Power conditioner			
Blower and motor cooling			
VFD cooling			
Additional components not listed included as forming the blower package			

as a test-specific checklist to define components that shall be included or excluded from the performance boundary and agreed upon between the parties to a test.

The package test shall include all electric-power-consuming devices, measured collectively or separately, identified and summed as the package electric power consumption. Individual power consumers shall be agreed to and noted in the test report defined in Section 6.

The electric performance boundary includes components within the test boundary and outside the test boundary.

In some cases, the electric performance boundary may exclude components within the test boundary: for example, a shop VFD that is not part of the delivered package but is used for the purpose of matching shop test conditions to specified site conditions.

3-5.3 Test and Specified Thermodynamic Properties

The physical and thermodynamic properties of the specified and test gas (air) shall be determined through the equations of state detailed in Section 5. The option of using tabulated data or an equation of state correlation as a source for these properties shall be agreed upon prior to the test. For more information, see Nonmandatory Appendix H.

The physical and thermodynamic properties of the specified and test air that shall be determined from the ambient temperature, pressure, and inlet moisture content (RH) throughout the expected pressure and temperature range, and that shall be known or accurately determined, are

(a) molecular weight
(b) specific heat at constant pressure
(c) ratio of specific heats
(d) viscosity
(e) isentropic exponent

The test speed shall be selected to operate the blower at the inlet volumetric flow rate and isentropic head (or pressure ratio for PD blowers) that are determined through examination of the specified performance and operating conditions. The test speed shall not exceed the safe operating speed of the blower and shall be maintained within the mechanical limits of the blower package.

Consideration should be given to critical speeds of rotating equipment in selecting the test speed.

Test pressures and temperatures shall not exceed the maximum allowable pressures and temperatures for the blower and motor.

Table 3-5.4-1 Permissible Deviations of Similitude Parameters for a Test of Dynamic Blowers

	Limit of Test Values as % of Specified Values	
Parameter	**Min.**	**Max.**
Specific volume ratio, v_i/v_d	95	105
Inlet volumetric flow rate, q_v	99	101
Isentropic head, W_s	100	101
Machine Mach number, M_m	See Figure 3-5.4-1	

GENERAL NOTE: In cases where the package available power may be exceeded during a test due to inlet conditions of the ambient test environment, refer to para. 3-5.4.1.

3-5.4 Permissible Deviations Between Test and Specified Operating Conditions

This Code defines one classification of test, which is based on the deviations between test and specified operating conditions. Tests shall be conducted with ambient air as the specified and test gas. Deviations of operating conditions and properties of air between the specified and the test performance conditions shall be subject to the following limitations: the individual and combined effects shall not exceed the limits of Table 3-5.4-1 for dynamic machines or Table 3-5.4-2 for PD machines.

The specified gas and test gas may differ by conditions; this should be noted in the test report. To maximize accuracy of test results, test conditions should duplicate specified operating conditions as closely as possible. Calculation procedures are given in Section 5 for gases conforming to Ideal Gas Laws.

Maintaining the pressure ratio within the limits of Table 3-5.4-2, adjust the blower speed to achieve the highest inlet volumetric flow rate obtainable at the test conditions within the allowable limits of the blower motor and record the performance data. See para. 5-4.5.1. Use this data to plot wire-to-air power vs. flow rate at the specified pressure ratio. Use this plot to extrapolate the wire-to-air power at the target inlet volumetric flow rate and pressure ratio using a nonzero intercept method.

Deviations from the above procedure and/or modifications to the blower package to accommodate the test should be agreed upon by the parties. It is recommended that the end user and/or specifying engineer consider the inherent uncertainty in prediction and measurement of blower performance and include appropriate tolerances on flow and power based on the process requirements. This consideration of tolerances is particularly important for fixed-speed machines that provide negligible adjustment of performance on the test stand. The machine specifications should clearly state allowable tolerances, especially regarding inlet flow, to ensure that the manufacturer considers these tolerances and provides appropriate factors of safety in the machine selection.

Note that the use of a shop VFD with PD blower systems specified to operate at constant speed solely to compensate for deviations between inlet volumetric flow rates at specified conditions and inlet volumetric flow rates at test conditions is not permitted. In this case, the flow rates shall be based on actual operating speed of the test system at the specified electric power frequency. Power projected for specified conditions shall be calculated using the method identified in para. 5-4.4.1.

Figure 3-5.4-1 Allowable Machine Mach Number Departures for Dynamic Blowers

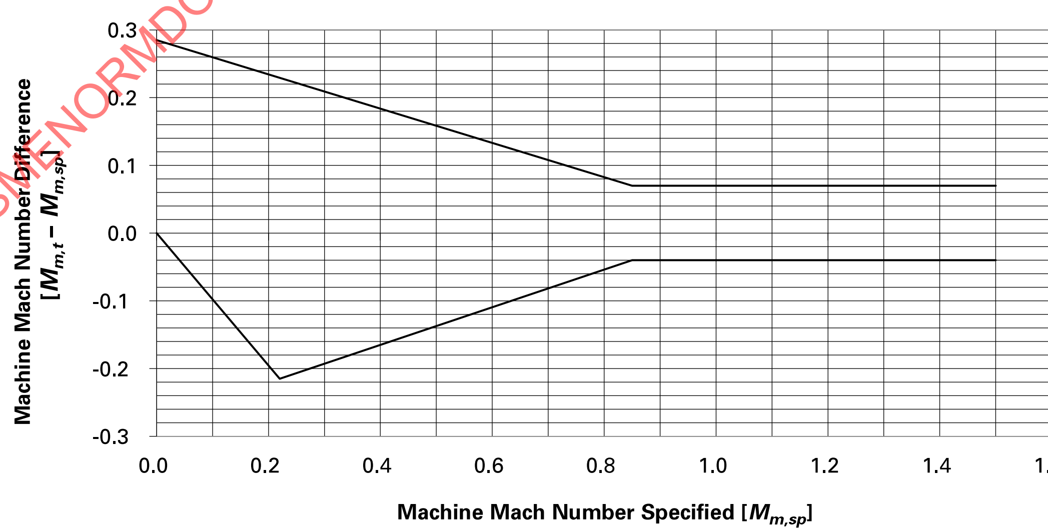


Table 3-5.4-2 Permissible Deviations of Operating Conditions for Positive Displacement (PD) Blowers

Parameter	Limit of Test Value as % of Specified Value for Constant-Speed PD Blowers		Limit of Test Value as % of Specified Value for Variable-Speed PD Blowers	
	Min.	Max.	Min.	Max.
Pressure ratio	100	102	100	102
Inlet volumetric flow rate [Note (1)]	100	110	98	102

NOTE: (1) There may be situations where it is not possible to achieve the target inlet volumetric flow rate within the deviation indicated above due to differences between the specified and actual test densities and power limitations of the blower package. For PD blowers, this may be addressed by referring to para. 5-4.5.1.

3-5.4.1 Operational Speed Deviation. In cases where the package available power may be exceeded during a test due to inlet conditions of the test air and environment, the following considerations shall be conformed to in lieu of operating outside the limits of the blower system power.

For dynamic blower packages, a deviation of operational speed at test conditions shall fall within a range of (as percent design values)

$$0.96 \le \left(\frac{N_t}{N_{sp}}\right) \le 1.04 \tag{3-5-1}$$

The permissible deviations provided in Table 3-5.4-1 shall prevail as follows (as percent of design values):

Inlet volumetric flow rate

$$0.99 \cdot q_{v,sp} \cdot \left(\frac{N_t}{N_{sp}}\right) \le q_{v,t} \le 1.01 \cdot q_{v,sp} \cdot \left(\frac{N_t}{N_{sp}}\right) \tag{3-5-2}$$

Isentropic head

$$1.00 \cdot W_{s,sp} \cdot \left(\frac{N_t}{N_{sp}}\right)^2 \le W_{s,t} \le 1.01 \cdot W_{s,sp} \cdot \left(\frac{N_t}{N_{sp}}\right)^2 \tag{3-5-3}$$

In such cases, the blower system shall be operated at the maximum speed permissible within the operation limits of the blower package.

To verify the correct test speed was selected for the operating conditions, and resulting test volumetric flow rate and isentropic head collected during test, use the following equations:

Volumetric flow rate rotation speed check

$$N_{sp} = N_t \cdot \left(\frac{q_{v,sp}}{q_{v,t}}\right) \tag{3-5-4}$$

Isentropic head rotation speed check

$$N_{sp} = N_t \cdot \sqrt{\left(\frac{W_{s,sp}}{W_{s,t}}\right)} \tag{3-5-5}$$

For configurations with a piped inlet or allowable by design, an inlet throttle device may be utilized to reduce inlet density of the blower package to maintain within operational limits. The inlet paths in such cases shall not affect the field operational configuration. Inlet configuration in all cases shall follow the guidance of para. 4-3.5.

3-5.5 Test Point Data Collection

When all variables have stabilized, the test personnel shall take the first set of readings of all essential instruments. A minimum of three sets of readings shall be taken during each test point.

The minimum duration of a test point, after stabilization, shall be 15 min from the start of the first set of readings to the end of the third set of readings. The three readings for each test point shall be within the fluctuation tolerances listed in Table 3-5.5-1.

A test point considers one complete set of instrument readings obtained in a 1-min period. The individual readings recorded in a 1-min period are summed and divided by the total number of readings to establish an average. This average is then used as the test point data.

3-5.6 Performance Curve Data Collection

When performance curves are required by specific agreement between the parties to verify the complete blower range of operation, a multipoint test should be performed. For a variable flow machine, one or more sets of 5-point (minimum) curves are collected over a

Table 3-5.5-1 Permissible Fluctuations of Test Readings

Measurement, Symbol, Units	Fluctuation (%) [Note (1)]
Inlet pressure, p_i, psia	2
Inlet temperature, T_i, °R	0.5
Discharge pressure, p_d, psia	2
Differential pressure of flow-measuring device, Δp, psi	1
Flow device temperature, T, °R	0.5
Relative humidity, RH, %	2
Wire power, P, kW	1
Line voltage, V, volts	2
Speed, N, rpm	1

GENERAL NOTE: The fluctuations follow Tables 3-5.4-1 and 3-5.4-2.

NOTE: (1) A fluctuation is the percent difference between the minimum and maximum test reading divided by the average of all sets readings for one test point.

selected range of operation. A point shall be taken at approximately the specified volumetric flow rate. The additional points should consist of one point near surge, two points between specified volumetric flow rate and surge, and one or more points at volumetric flow rates higher than the specified point, including the maximum volumetric flow rate point. PD blowers shall utilize the maximum operating pressure as the "surge" condition. The proximity between points and total number shall be as agreed between client and supplier.

For dynamic blowers, the performance curve should plot pressure vs. flow and power vs. flow using units as agreed between the parties.

Variable-speed PD blowers should plot flow vs. speed and power vs. speed and/or flow vs. power at constant pressure, using units as agreed between the parties. PD blower plots should include one point near the minimum flow as limited by differential temperature and one point near the maximum flow as limited by the lower of motor power, speed, or pressure.

Refer to Nonmandatory Appendix F for examples.

3-5.7 Establishing Minimum Continuous Flow

For every specified point of operation tested, the minimum continuous flow prior to surge for the associated speed, vane, or inlet valve condition (inclusive) should be determined when required by specific agreement between the parties.

Considering dynamic blowers, the flow at which surge occurs can be determined by slowly reducing the flow rate at the test speed until indications of unstable or pulsating flow appear. The severity of surge will vary widely as a function of pressure ratio, type of blower, and capacitance of the piping system. Surge may be identified by noise, fluctuations in the differential pressure of the flow nozzle, or a drop and/or fluctuation of the pressure and/or temperature.

When the surge flow has been identified, the flow should be increased slightly until stable operation is restored (minimum continuous flow) so that a complete set of performance data may be taken. This process may be repeated a second time to demonstrate the reliability of the initial setting.

Location of the surge condition as defined above and agreed between parties shall be determined for a given operating point with the surge protection system engaged for at least a portion of the test. The speed and vane or inlet valve condition for a given operating point shall be maintained for surge verification. Record all measured data points for this condition.

It should be understood that a surge flow established in a shop test may not define the surge conditions which will occur in the field due to differences in piping configuration and system response.

3-5.8 Establishing Maximum Continuous Flow

For every specified point of operation tested, the "choke flow," or maximum continuous flow for the associated speed, vane, or inlet valve condition (inclusive), should be determined when required by specific agreement between the parties.

Considering dynamic blowers, the choke flow should be determined by gradually opening the discharge throttle valve while maintaining speed and inlet pressure until the flow remains essentially constant with decreasing discharge pressure. Record all measured data points for this condition.

If choke flow is to be determined, the facilities shall be designed so as not to limit maximum flow. This shall be performed within the mechanical limits of the machine under test.

3-5.9 Inconsistent Measurements

If any measurement influencing the result of a test is inconsistent with some other like measurement, although either or both of them may have been made strictly in accordance with the rules of the individual test code, the cause of the inconsistency shall be identified and eliminated.

Where four independent instruments are used to measure a pressure or temperature value and one recorded observation is inconsistent due to measurement error, its value shall be discarded and the value determined from the average of the other three. Where fewer than four independent measuring devices are used, all values shall be used and averaged to determine the measurement value.

3-5.10 Errors and Uncertainties

It should be recognized that the results of the test calculations are subject to error caused by the inaccuracies of the test instruments and/or procedures. An uncertainty analysis should be made prior to the test to assure that the test objectives can be met. The detailed procedures are given in ASME PTC 19.1 and are discussed in Section 7.

The uncertainty is a measure of the quality of the test and should not be used as a measure of the quality of the machine.

3-5.11 Piping

Piping arrangements required to conduct a test under the Code are detailed in Section 4. Permissible alternates are described for convenience and suitability. A selection suitable for the prevailing test conditions shall be made and described in the test report.

Minimum straight lengths of piping at the inlet, discharge, and on both sides of the flow device are specified in Section 4.

When blowers are treated as a number of individual sections, these piping requirements apply to each section. Such piping between sections may not occur naturally in the design. When it does not, the parties of the test should elect by mutual agreement which sections and components are to be included in the Thermodynamic Test Reference Boundary and the Performance Boundary.

3-6 RECORDS

3-6.1 Data Records and the Test Log

The test log shall identify the blower system manufacturer, model, and serial number. Test location, driver identification, test instruments used, and test date shall be listed. Raw data for each test point shall be recorded as observed, along with the time each set of data is recorded. Corrections and corrected readings shall be listed separately in the test report.

At the completion of the test, the log and complete set of test data shall be signed by the representatives of the interested parties. Copies of all shall be furnished to the interested parties. The test report shall be completed in accordance with the instructions in Section 6.

For all acceptance and other official tests, a complete set of data and a complete copy of the test log shall become the property of each of the parties to the test. The original log; data sheets, files, and disks; recorder charts; tapes; etc., being the only evidence of actual test conditions, shall permit clear and legible reproduction. Copying by hand is not permitted. The completed data records shall include the date and time of day the observation was recorded. The observations shall be actual instrument readings, with conversion to engineering units based on calibration instrument scaling. Adjustments to readings to compensate for calibration errors, instrument deficiencies, or DAQ deficiencies are not permissible, except as agreed to by all parties. The test log should constitute a complete record of events including details that at the time may seem trivial or irrelevant. Erasures on, or destruction or deletion of any data record, page of the test log, or any recorded observation is not permitted. If corrected, the alteration shall be entered so that the original entry remains legible and an explanation is included. For manual data collection, the test observations shall be entered on carefully prepared forms that constitute original data sheets authenticated by the observer's signature. For automatic data collection, printed output or electronic files shall be authenticated by the engineer in charge and other representatives of the parties to the test. When no paper copy is generated, the parties to the test must agree in advance to the method used for authenticating, reproducing, and distributing the data. Copies of the electronic data files must be distributed to each of the parties to the test immediately upon completion of the test. The data files shall be in a format that is agreeable between all parties. Data residing on a machine should not remain there unless a backup, permanent copy is made.

3-6.2 Analysis and Interpretation

During the conduct of a test, or during the subsequent analysis or interpretation of the observed data, an obvious inconsistency may be found. If so, reasonable effort should be made to adjust or eliminate the inconsistency. Failing this, test runs should be repeated.

Section 4
Instruments and Methods of Measurement

4-1 GENERAL CONSIDERATION

4-1.1 Instrument Selection

Instrumentation is required to determine the inlet and discharge gas states, flow rate, blower speed, and package power consumption. The selection of instrumentation shall be determined by the uncertainty limit requirements of the test as well as by the suitability for the test conditions. The instrument selection shall be justified by calculation that the uncertainty in results meets the stated test objectives.

4-1.2 Calibration Certificates

Calibration certificates shall be available for all test instruments used and shall be dated within the previous 12 months. Calibration shall be traceable to a recognized national or international standard. Refer to ASME PTC 19.1 for additional guidance. A test stand utilizing data collection equipment shall be calibrated to insure that both the primary element and any interface containing an analog to digital conversion is included as either a composite or a separate calibration.

4-2 POWER

This subsection gives instructions for accurately determining the input power quantities required to operate the blower system being evaluated in whatever form is required. Although electric power is typically predominant, all power input to the blower system shall be converted to kilowatts and added together. All energy entering the system boundary shall be accounted for, including power required for secondary cooling systems including but not limited to pumped cooling liquid mechanical energy. Refer to para. 3-5.2 for more details.

The choice of method and instruments, required calculations, and corrections to be applied in any given case shall depend on the purpose of the measurement, the accuracy required, and the nature of the circuit to be measured.

This subsection shall not supersede the guidance or requirements of any ASME or IEEE standard. The intent is to simplify the requirements for these measurements as they apply to this Code's tests and to provide a common platform for power measurement across different technologies evaluated. This Code requires the determination of power supplied to the blower system. The power required to operate the blower system at any given test point shall be deemed as the cumulative power entering the system boundary of the blower.

The methods given herein include direct determinations of active power (kilowatts), volt-ampere reactive power (var), and power factor (*pf*) consumed in alternating-current single-phase and polyphase electric circuits. This subsection also gives guidance for the calculation of ancillary devices required to operate the blower system. This subsection does not include such measurements of fundamental electric properties as voltage, current, frequency, resistance, and impedance, except as needed to support the objectives of this document.

4-2.1 Wire Power Measurement Technique

Electric system parameters required for the execution of this Code include cumulative gross electric input, power factor, power to other auxiliary system electric loads, and associated power factor values. Blondel's theorem for the measurement of electric power or energy states that in an electric system of n conductors, $n - 1$ metering elements are required to measure the true power or energy of the system. Therefore, the metering methods required for use on each of the following systems are:

(a) two-wire systems — one single-element meter

(b) three-wire systems — two single-element meters or one two-element meter

(c) four-wire systems — three single-element meters or one three-element meter

4-2.1.1 Power Analyzer Method. The type of instrumentation approved in determining input power of the performance test results is a high-accuracy power analyzer. Other methods of power measurement contain tolerance errors that can contribute unnecessary uncertainty to the result. At a minimum, the power analyzer shall have the capability to measure voltage, current, active power, and power factor.

The power analyzer can also provide other measurement parameters such as volt-ampere (VA), var, and frequency. Some power analyzers permit measuring and displaying all three currents and all three voltages of a three-phase motor simultaneously.

Note that all power measurements shall be made at the input supply to the blower assembly. Measurements shall not be taken after any power factor correction circuitry and/or variable frequency drives (VFD). See Figures 4-2.1.1-1 and 4-2.1.1-2.

4-2.1.2 Minimum Accuracy and Function Requirements of Power Analyzer. Table 4-2.1.2-1 references the minimum requirements for power analyzers by accuracy and function. All accuracies are between a frequency range of 10 Hz and 7 kHz.

CAUTION: The voltage, current, and frequency ratings of the power analyzer must be within the scope of the equipment being tested, and the instrumentation must have an appropriate resolution of measurement.

4-2.1.3 Calibration of Power Analyzer. Power analyzer instrumentation should be calibrated in accordance with the manufacturer's specifications and procedures. Standard instruments and calibration sources should have a higher accuracy than the measuring instrument being calibrated. All standard instruments and calibration sources should be under a primary calibration schedule and should have calibration records traceable to a recognized national or international standard.

For power meters that produce analog output, calibration shall include full-loop calibration from the source inputs to the output method used during the test.

4-3 PRESSURE

4-3.1 Pressure Measurement Standards

Pressure calibration instruments shall have an accuracy of ±0.030% of reading and a resolution of 0.1 times the accuracy. Pressure measurement instruments used for calibration shall be certified by a national or international standard.

4-3.2 Pressure Measurement Selection

Acceptable pressure measurement instruments shall include Bourdon tube gauges, transducers, transmitters, liquid column manometers, impact tubes, Pitot static tubes, barometers, and other devices described in ASME PTC 19.2.

The selection of instrumentation shall be determined by the uncertainty limit requirements of the test as well as suitability for the test conditions. The instrument selection shall be justified by calculation that the uncertainty in results meets the stated test objectives.

4-3.3 Instrument Verification

If programmable instruments are used for any readout at a given measuring station, or if a DAQ is used, at least one parallel, local, direct readout of a nonprogrammable measurement device shall be provided for verification of reading. As an alternative, a programmable, local, direct-reading instrument may be used if a master instrument is used to calibrate the verification instrument at the time of the test. Means shall be provided to verify the accuracy of the primary transducer signal to the displayed engineering units. The verification instrument shall be in place of one of the instruments required by this Code. The permissible deviation of the verification instrument shall be 2 times the total of the absolute values of the specified accuracy of the two types of independent instruments, unless another agreement is made between all parties.

4-3.4 Pressure Measurement Averaging

Where multiple independent instruments are used to measure a pressure and one of the measurements is inconsistent due to measurement error, its value shall be discarded and the value determined from the average of the other readings.

4-3.5 Pressure Measurement Locations

For pressure measurements in piping, at each pressure measurement location, four separate instruments shall be installed with measurements located at 90-deg increments around the pipe circumference, or as detailed for the measurement location. The four measuring taps may be tied together (i.e., manifold) to create an average. The pressure instrumentations shall be indexed 45 deg from adjacent temperature measurement locations. The location of the pressure measurement stations has a specific relation to the inlet (p_i) and outlet (p_d) sections of the blower. The instrument tubing size shall match the tap size. Guidance for minimum lengths of straight pipe is provided in Figures 4-3.5-1 through 4-3.5-4. The appropriate figure shall be selected and indicated in the test report. Concentric expansion cones and flexible connectors may be considered as straight pipe in calculating dimensions for Figures 4-3.5-2 and 4-3.5-4.

4-3.6 Pressure Measurement Instrument Types

Refer to ASME PTC 19.2 for supplemental information on instruments to measure pressure. When pressure transducers and other pressure measurement devices are used, these instruments shall be calibrated as described in ASME PTC 19.2. Where gauge lines are filled with liquids, provide means to measure the liquid level, and a correction shall be applied for the unbalanced liquid head.

If requested, in addition to calibration certificates, verification of pressure instrument calibration shall be conducted at the time of the blower performance test. Dead-weight gauges, manometers, or air calibrators can be used to verify instrument conformity with provided calibration. If the verification procedure shows the pressure instruments are not properly calibrated, either the pressure instruments should be recalibrated or the test

Figure 4-2.1.1-1 Power Analyzer Connection (Single Point)

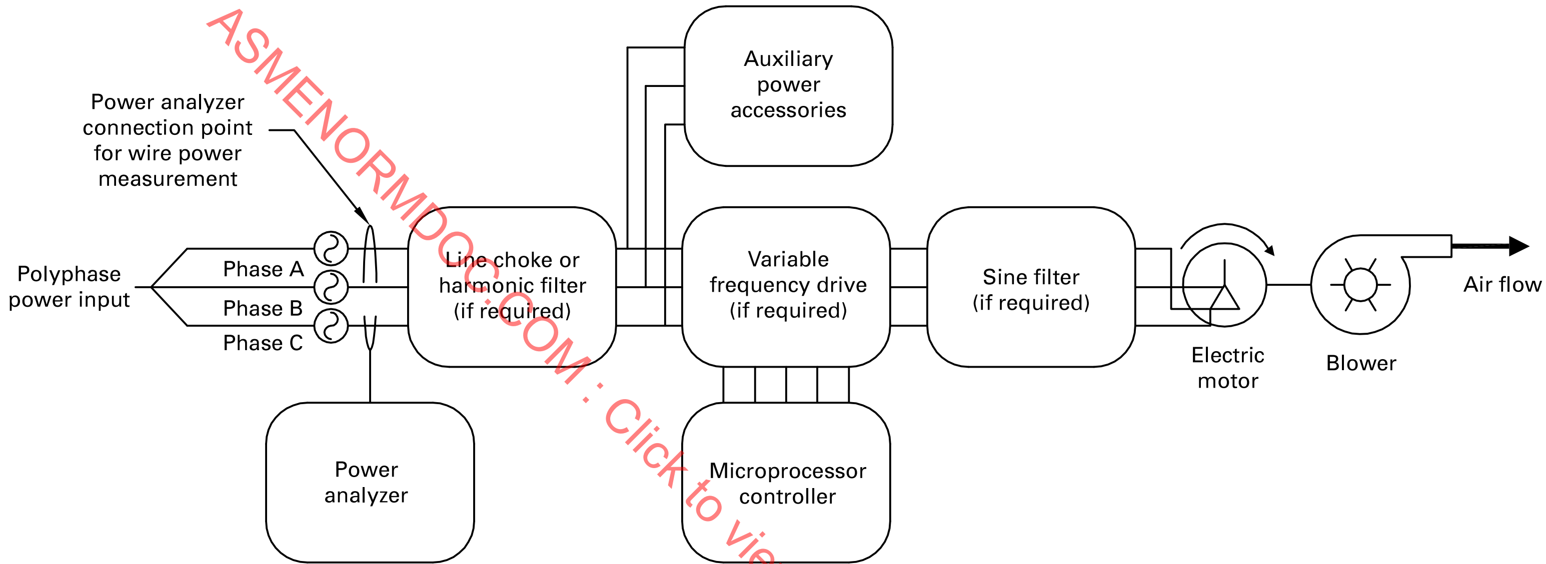


Figure 4-2.1.1-2 Power Analyzer Connection Including Secondary/Additional Power Feed

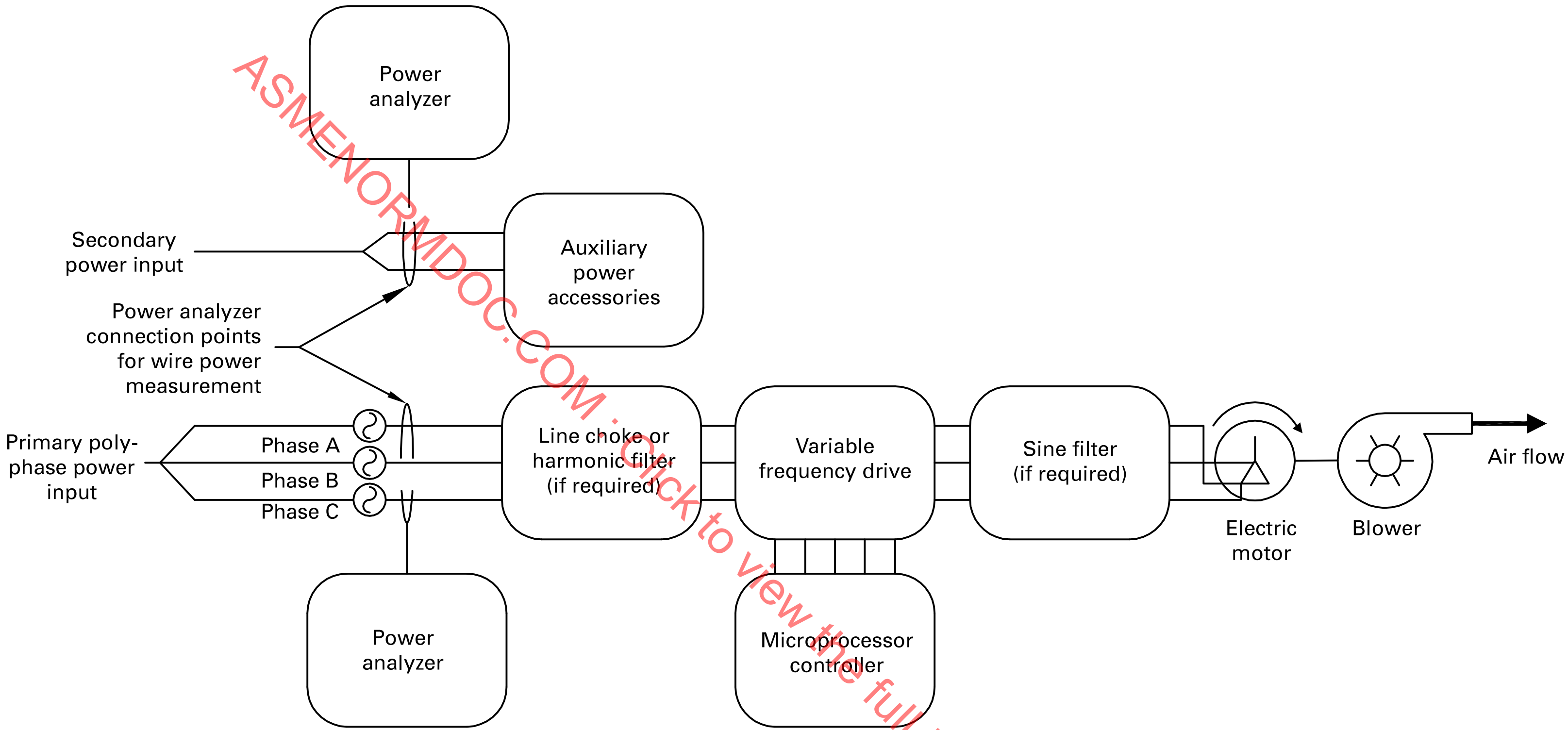
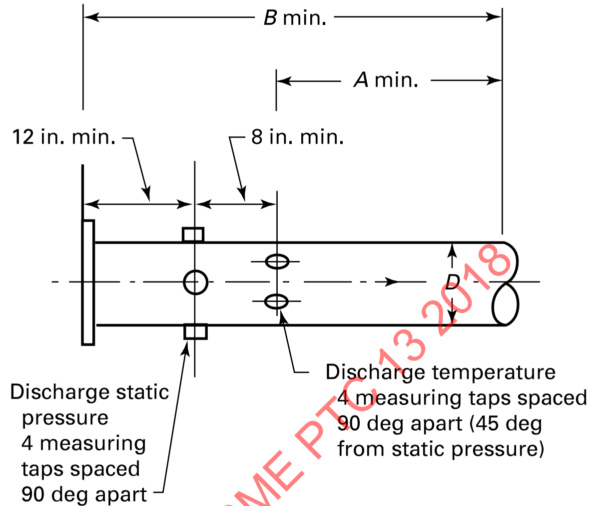


Table 4-2.1.2-1 Minimum Accuracy and Function Requirement of Power Analyzer

Parameter	Value
Basic power, W, VA, VAR [Note (1)]	±0.2% of reading, ±0.1% full scale per phase
Voltage (potential) transformer (PT)	±0.3% of reading, ±0.05% full scale (600 V)
Current transducer (CT)	±0.3% of reading, ±0.05% full scale (500 A)
Power factor [Notes (2) and (3)]	±0.1 *pf*
Sampling rate	1,089 samples/cycle 50k samples/sec
Frequency range	30 Hz to 70 Hz, ±0.2% of reading
Bandwidth	3 kHz for current, 7 kHz for voltage
Harmonics	1% reading, ±0.05% full scale per phase

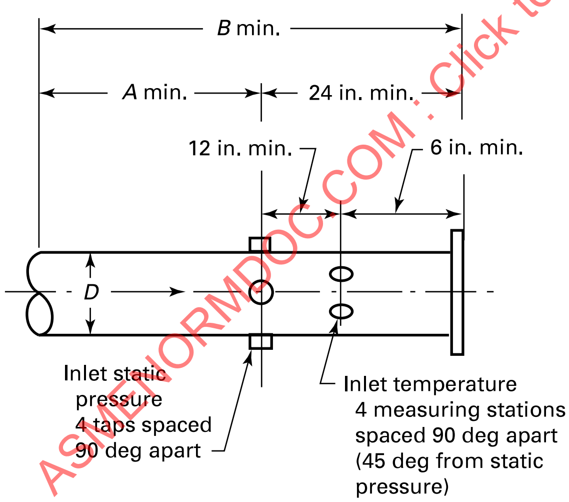
NOTES:
(1) If the auxiliary power is less than 5% of total performance power at the performance point being tested, a precision measurement instrument is not required for the auxiliary power measurement.
(2) Based on 50 Hz/60 Hz line frequency.
(3) Only applicable if power factor is used with voltage and amperage to calculate power. Power factor is not applicable if power is directly measured using a power analyzer.

Figure 4-3.5-2 Discharge Configuration



Discharge Opening Followed by	Minimum Dimension *A*	Minimum Dimension *B*
Straight run	2*D*	3*D*
Elbow	2*D*	3*D*
Reducer	3*D*	5*D*
Valve	3*D*	5*D*
Flow device	8*D*	10*D*

Figure 4-3.5-1 Inlet Configuration



Inlet Opening Preceded by	Minimum Dimension *A*	Minimum Dimension *B*
Straight run	2*D*	3*D*
Elbow	2*D*	3*D*
Reducer	3*D*	5*D*
Valve	8*D*	10*D*
Flow device	3*D*	5*D*

results should be adjusted by the amount of the difference. The decision on the course of action shall be agreed to by all parties. When a DAQ is utilized for recording, the instruments, verified from the source to the acquisition readout/recording system, shall include all analog to digital conversions in the measurement and acquisition chain, and shall be within the permissible deviations as stated herein.

Where pulsations are anticipated, pressure snubbers shall be used. Pressure snubbers are recommended for PD blower pressure measurement. Orifice type or porous element type snubbers are acceptable. The snubber shall be installed in the pressure instrument tubing close to the instrument. Refer to ASME B40.100-2013 for more information.

4-3.6.1 Bourdon Tubes. Bourdon tubes or similar gauges should be selected to operate in the midrange of the scale. The diameters of the scales and the arrangement of the graduations shall be readable. The temperature of the gauge during calibration, either as listed on the calibration certificates or as performed at time of test in the blower test lab, shall be within 40°F of the indoor ambient temperature prevailing during the test.

4-3.6.2 Manometers. Manometers can be either U-tube or single-leg design. Scales shall be engraved in inch graduations with a resolution of 0.1 in. of water or better. Tubes shall be of appropriate length and

Figure 4-3.5-3 Vortex Producing Axial Inlet

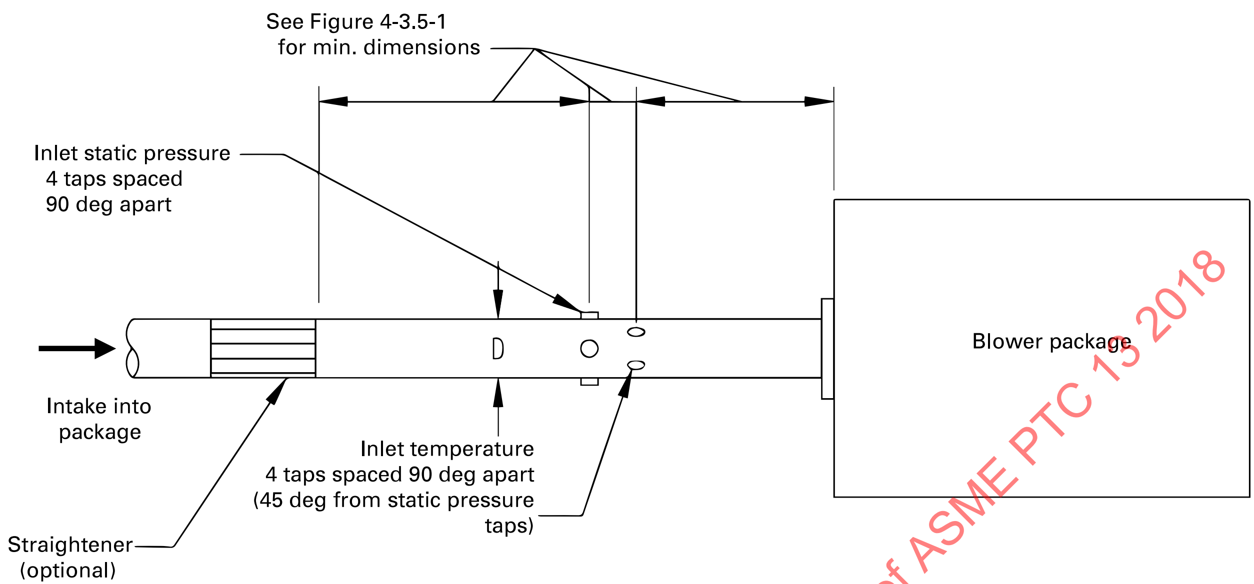


Figure 4-3.5-4 Diffusing Volute Discharge With Nonsymmetric Flow

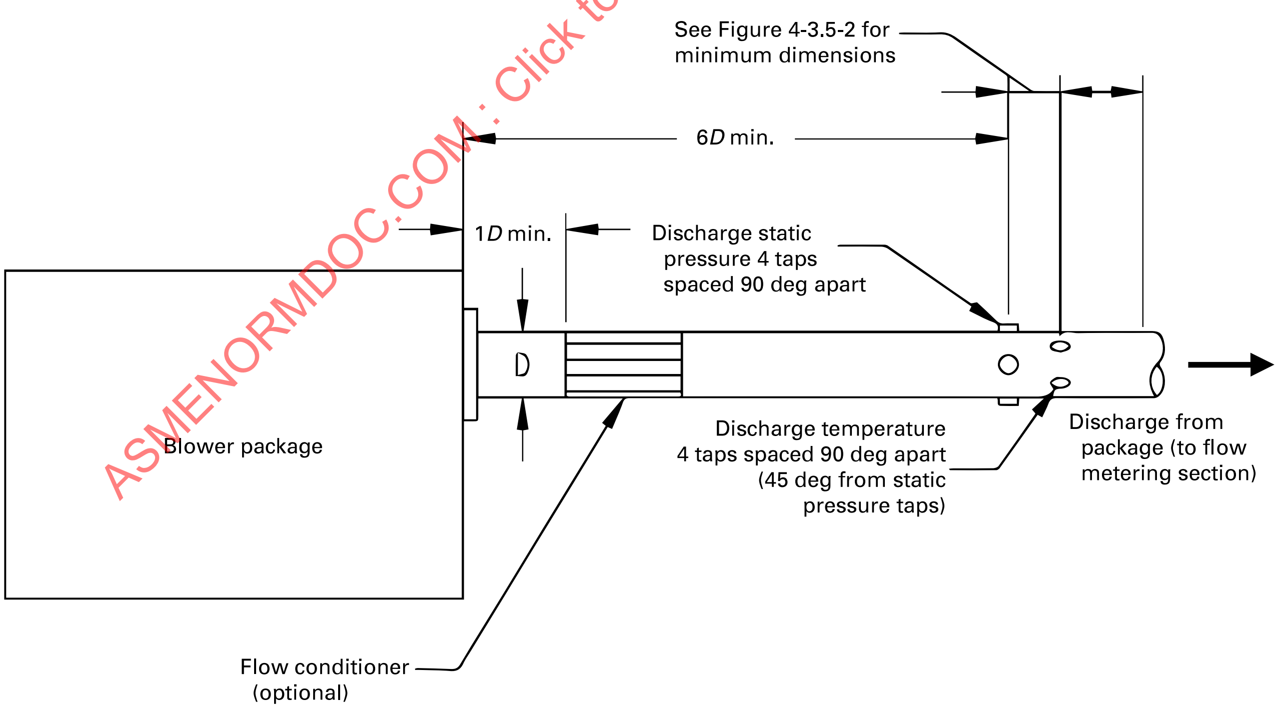
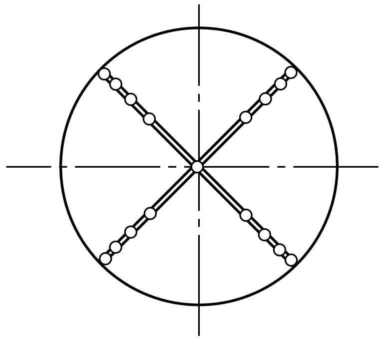
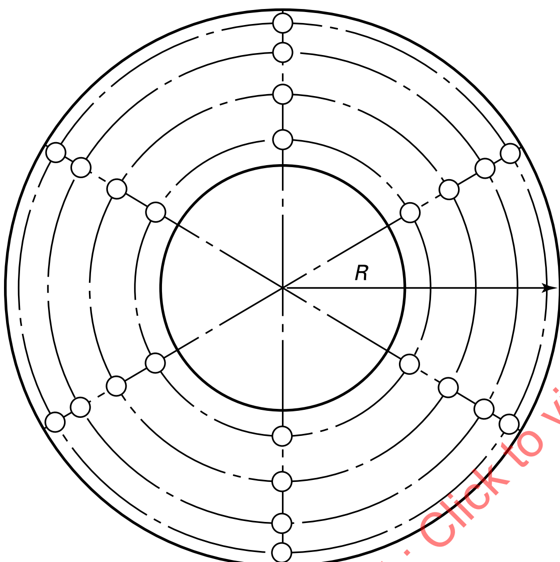


Figure 4-3.7-1 Pipe Velocity Measurement Loci



Stationary array mounted on crossbars in a circular conduit



fluids of suitable specific gravity to permit easy reading of differentials within 0.5% of the reading. Small-bore manometers less than $\frac{1}{2}$ in. are subject to appreciable error resulting from capillary forces, variable meniscuses, and restricted separation of entrained gas bubbles. These errors vary with the type of fluid, the tube diameter, and the tube cleanliness. Correction tables for meniscus error shall be used for tube bores less than $\frac{1}{2}$ in. Single-leg manometers shall have both liquid levels visible with a means for adjusting the scale to zero position while the instrument is in use. Single-leg manometers shall be checked for zero position before and after the test. Manometer fluid shall be chemically stable when in contact with air and metal parts of the instrument.

The specific gravity and the coefficient of thermal expansion of the fluid shall be determined before the test. See ASME PTC 19.2 for further guidance.

4-3.6.3 Transducers and Transmitters. Pressure transducers and transmitters shall be selected with pressure ranges appropriate for the expected test pressures. It is recommended these instruments be selected to operate in the midrange of the scale, from 20% to 80% of full scale; this shall be agreed upon between all parties pending review of calibration certificates verifying linearity within the selected usage or operating range. Differential pressure transmitters may be selected to operate in the range of 5% to 95% of full scale if a valid calibration certificate verifies linearity within this range.

Ring manifolds are permissible if separate transmitters for each instrument are utilized.

4-3.7 Velocity Pressure

Velocity pressure shall be either computed on the basis of average velocity, as calculated in accordance with Section 5, or determined by a Pitot tube traverse of two stations. The average shall be the ratio of the measured volume rate to the pipe area of the measuring station. To utilize the average velocity method, the computed discharge-side velocity pressure must be below 5% of the absolute static pressure. Otherwise, the Pitot tube traverse method shall be used. For each station, the traverse shall consist of ten readings at positions representing equal areas of the pipe cross section as shown in Figure 4-3.7-1, with suitable design modifications for adaptation to prevailing pressure, velocities, and pipe sizes.

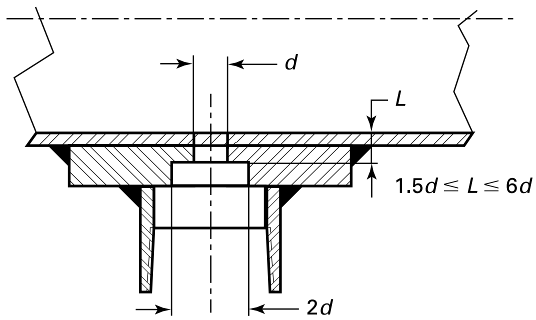
4-3.8 Static Pressure

Static pressure shall be taken as the arithmetic average of individual raw data observations from the number of measuring instruments utilized, spaced 90 deg in the same plane of the pipe perpendicular to the axis of flow. The error associated with different tap geometries described in ASME PTC 19.2 shall be taken into consideration. The diameter of the outer pressure tap shall be twice that of the inner pressure tap. The wall thickness, including any reinforcement, shall be greater than 1.5 times the inner tap diameter and less than 6 times the inner tap diameter. The hole shall be drilled normal to the pipe surface (perpendicular) and shall be free of burrs. A preferred connection is obtained by welding a half coupling to the pipe and then drilling the hole. The Mach number should be less than 0.2 and the velocity pressure less than 5% at the instrument location. Refer to Figure 4-3.8-1 for pressure tap installation in thin-wall piping.

4-3.9 Total Pressure

In cases where the velocity pressure guidance in para. 4-3.8 is not met, total pressure probes shall be used to measure pressure at the same stations where the static measurements are made. Where the absolute values from the number of stations utilized differ by

Figure 4-3.8-1 Reinforced Pressure Tap for Thin Wall Piping



Pressure Tap for Thin Wall Piping

more than 1.0%, the cause shall be determined and the condition corrected. See ASME PTC 19.2 for further guidance as well as guidance for gauge snubbers.

4-3.10 Inlet Pressure

Inlet pressure is the total pressure prevailing at the blower package inlet. It is the sum of the static pressure and the velocity pressure. Static pressure shall be measured as specified for inlet pipes in para. 4-3.5.

Where no inlet pipe is used, as in Figure 4-3.10-1, the inlet total pressure shall be measured by four separate instruments. The face inlet velocity shall be less than 1,000 ft/min at rated airflow at the point of measurement. Barometric pressure is equivalent to inlet pressure in this case, provided the barometric pressure instrument is in the vicinity of the blower package inlet and free of the effects of velocity.

Total pressure should be directly measured by the use of total-pressure probes inserted into the flow stream (such probes shall be properly oriented or directionally compensated to ensure proper measurement). The measurement obtained by a total-pressure probe can be influenced to varying extent by spatial location. In the event of significant unresolved differences from the total pressure deduced from the static pressure and average velocity, the static-pressure-based result shall prevail.

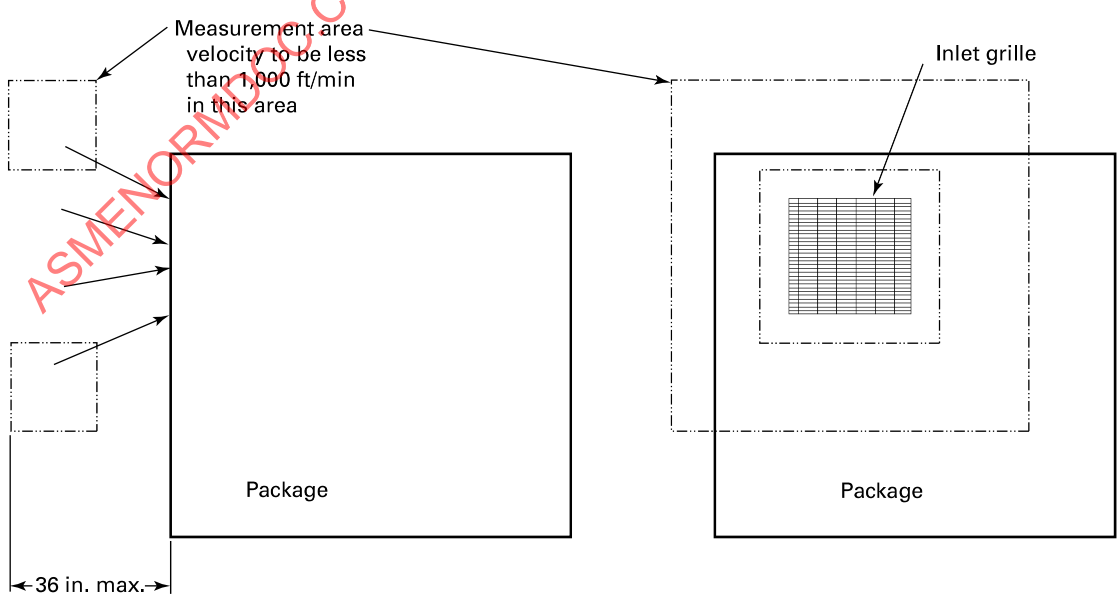
If more than one process air inlet to the package is provided, the pressure measurement setup shall be duplicated at each inlet. The overall package inlet pressure shall be averaged proportional to the flow area through each inlet, in accordance with the following equation for the example of two inlets:

$$p_i = \left(\frac{A_1}{A_1 + A_2}\right)p_1 + \left(\frac{A_2}{A_1 + A_2}\right)p_2 \qquad \text{(4-3-1)}$$

4-3.11 Discharge Pressure

Discharge pressure is the total pressure prevailing at the blower discharge. It shall be taken as the sum of the static pressure and the velocity pressure. Static pressure shall be measured as illustrated in Figures 4-3.5-2 and 4-3.5-4.

Figure 4-3.10-1 Package Inlet



Total pressure may be directly measured by the use of total pressure probes inserted into the flow stream. When used, such probes shall be properly oriented to insure proper measurement.

The measurement obtained by a total-pressure probe can be influenced to varying extent by spatial location. In the event of significant unresolved differences from the total pressure deduced from the static pressure and average velocity, the static-pressure-based result shall prevail.

If an optional flow conditioner is used, the measured static pressure must be adjusted to account for the pressure drop through the flow conditioner by adding the pressure drop through the flow conditioner to the absolute static pressure measured downstream of the flow conditioner:

$$p_d = p_{d,\text{meas}} + k \cdot \frac{\rho_d v_d^2}{2g_c} \tag{4-3-2}$$

Refer to Table 4-5.3-1 for values of k.

4-3.12 Ambient Pressure

Ambient pressure shall be recorded at the beginning of each test point. The instrument(s) shall be located at the air source for the test. The instrument(s) shall be protected from weather and direct sunlight. A single barometer may be used for the barometric pressure readings. Alternatively, a single absolute pressure transducer and transmitter may be used.

4-3.13 Pressure Measurement Constraints

Test pressures shall not exceed the maximum allowable operating pressures for the blower.

4-4 TEMPERATURE

4-4.1 Temperature Measurement Standards

Dry block or liquid bath calibrators shall be used for temperature instruments. Accuracy shall be ±0.02°F (±0.01°C) and resolution shall be 0.01° Fahrenheit or Celsius. Temperature measurement instruments used for calibration shall be certified by a national or international standard.

4-4.2 Instrument Selection

Reference should be made to ASME PTC 19.3 for supplemental information on instruments to measure temperature. Temperature shall be measured by thermocouples, liquid-in-glass thermometers, resistance temperature detectors, or other devices with equivalent accuracy. The range of their scales, the sensitivity, and the required accuracy shall be selected to minimize uncertainty. Thermowells of the type indicated by ASME PTC 19.3 for a particular velocity may be used with temperature detectors as long as measurements achieve thermal stability prior to time of recording.

The selection of instrumentation shall be determined by the uncertainty limit requirements of the test as well as suitability for the test conditions. The instrument selection shall be justified by calculation that the uncertainty in results meets the stated test objectives.

4-4.2.1 Thermometer. If a liquid-in-glass thermometer is selected, it shall be installed in a thermowell. There may be a need for an emergent stem correction. Refer to ASME PTC 19.3 for further information.

4-4.2.2 Thermocouples. Thermocouples shall have junctions silver brazed or welded. The selection of materials shall be suitable for air within the temperature range being measured. Calibration shall be made with the complete assembly, including the instrument, the reference junction, and the lead wires. If the well is integral with the thermocouple, the well shall also be included in the calibration. Accuracy shall not be less than ±0.3°F (±0.15°C). Refer to ASME PTC 19.3.

4-4.2.3 Resistance Temperature Detector (RTD). Each RTD shall be a nominal 100 ohm-in., three- or four-wire, hermetically sealed, platinum resistance element. The sensing element shall be enclosed in an outer sheath. Accuracy shall be ±0.3°F (±0.15°C) over the specified operating range.

4-4.2.4 Thermometer Wells. Thermometer wells, if used, shall be as small in diameter and with walls as thin as conditions will permit. Wells shall be evaluated for the conditions of anticipated use to determine the time lag and the corrections to be applied. The temperature element should be spring loaded in the thermowell, or other means may be used to ensure thermal conductivity.

4-4.3 Instrument Verification

If programmable instruments are used for any readouts at a given measuring station, or if a DAQ is used, at least one parallel, local, direct readout of a nonprogrammable measurement device shall be provided for verification of reading. As an alternative, a programmable, local, direct-reading instrument may be used if a master instrument is used to calibrate the verification instrument at the time of the test. Means shall be provided to verify the accuracy of the primary transducer signal to the displayed engineering units. The verification instrument shall be in place of one of the instruments required by this Code. The permissible deviation of the verification instrument shall be 2 times the total of the absolute values of the specified accuracy of the two types of independent instruments unless another agreement is made between all parties.

4-4.4 Temperature Measurement Averaging

Where multiple independent instruments are used to measure a temperature value and one recorded observation is inconsistent due to measurement error, its value shall be discarded.

The number of instrument readings for each test point shall be within the fluctuation tolerances established herein. In no case shall fewer than two instruments be used.

4-4.5 Temperature Measurement Locations

At each temperature measurement location, four separate instruments shall be installed with measurements located at 90-deg increments around the pipe circumference, or as detailed for the measurement location. The temperature instrumentations shall be indexed 45 deg from adjacent pressure measurement locations. The locations of the temperature measurement stations have a specific relation to the inlet and outlet sections of the blower.

The immersion length shall be at least 30% of the pipe radius. Reference should be made to ASME PTC 19.3 for supplemental information. The instrument tubing size shall match the tap size.

4-4.6 Temperature Measurement

The following general precautions are recommended when making any temperature measurement:

(a) The instrument installation should assure that thermal conductance by radiation, convection, and conduction between the temperature-sensitive element and all external thermal bodies (pipe wall, external portions of thermometer wells and thermocouple, etc.) shall be negligible in comparison to the conductance between the sensor and the medium being measured. Insulation of those parts of the thermometer well, thermocouple sheath, etc. that extend beyond the pipe's outside diameter may be a means of accomplishing this objective if necessary.

(b) The pipe section from the discharge flange to the temperature measurement station and the flow measurement station shall be thermally insulated to minimize the thermal gradient in the flowing fluid. The piping insulation shall have a minimum thermal resistance of 12 hr · ft^2 · °F/Btu · in.

(c) To minimize the unavoidable conduction of heat, the temperature measuring device shall extend a sufficient distance into the fluid stream, it shall be at least 30% of the pipe radius, and it shall be installed perpendicular to the wall.

(d) Precaution shall be taken to avoid insertion of the temperature measuring device into a stagnant area when measuring the temperature of a flowing medium.

(e) Temperature measurement devices should be selected to operate in the midrange of the scale, 10% to 90% of full scale. Caution should be taken because some of these devices have a relatively slow response time. See para. 3-3.11 for thermal stability requirements between data points.

4-4.7 Total Temperature

Total temperature is the sum of static temperature and velocity temperature. Normally, the actual temperature measured is a value between static and total temperature. The velocity temperature is then corrected for the recovery factor and added to the measured observation. The recovery factor shall be provided by the instrument supplier and is further detailed in Section 5. Special temperature probes made to measure total temperature need little or no correction. For total temperature conversion, see para. 5-1.5.

4-4.8 Inlet Temperature

Inlet temperature is the total temperature prevailing at the blower package inlet. When the blower is tested with an inlet pipe, four temperature taps shall be spaced 90-deg apart and displaced 45 deg from the static pressure sensors (see Figures 4-3.5-1 and 4-3.5-3). Ambient and inlet temperatures shall be measured separately.

If the air source is from the room and no inlet piping is provided, the inlet condition shall be measured at the point where the airflow stream passes the boundary and the instruments shall be located as close as possible to the package, as long as the allowable deviation between instrument readings is met, and they shall be located in the inlet airstream. Precautions shall be taken to prevent negative pressures in the vicinity of the temperature instrument, which may be caused by strong winds, blower inlets, or ventilating fans. For test arrangements with no inlet piping, the inlet velocity shall be less than 1000 ft/min at rated airflow at the point of measurement. Ambient temperature is equivalent to inlet temperature in this case.

If more than one process air inlet to the package is provided, the temperature measurement setup shall be duplicated at each inlet. The overall package inlet temperature shall be averaged proportional to the flow area through each inlet in accordance with the following equation:

$$T_i = \left(\frac{A_1}{A_1 + A_2}\right)T_1 + \left(\frac{A_2}{A_1 + A_2}\right)T_2 + \cdots \tag{4-4-1}$$

The inlet conditions shall be measured at the point where the airflow stream passes the system boundary. Ambient temperature shall be measured separately with a single instrument as reference only for systems with piped inlets.

4-4.9 Discharge Temperature

Discharge temperature is the total temperature prevailing at the blower discharge. When a blower is assembled for test with a discharge pipe, the instruments shall be located as shown in Figure 4-3.5-2 or Figure 4-3.5-4, spaced 90-deg apart, and displaced 45 deg from the pressure taps.

When the values of raw data observations utilized differ by more than 0.5% of the absolute temperature, the cause shall be determined and corrected.

4-4.10 Temperature Measurement Constraints

Test temperatures shall not exceed the maximum allowable operating temperatures for the blower.

4-5 VOLUMETRIC FLOW RATE

4-5.1 Flow-Measuring Devices

Flow shall be measured by using a differential pressure-type device such as a concentric square-edge orifice, ASME flow nozzle, Herschel-type venturi tube, or alternate device of equal or better accuracy and in conformance with ASME PTC 19.5-2004. This Code is primarily focused on airflow measurement utilizing a square-edge orifice for a differential-type flow element. Reference shall be made to ASME PTC 19.5-2004 for general instruction and detailed description of the differential-type flow elements as provided in Sections 3, 4, 5, 6, and 7 for compressible fluids. The interested parties shall mutually agree upon the type of metering device to be used and the choice shall be stated in the test procedure and report.

An orifice type of differential pressure class meter consists of a flat plate through which the diameter, *d*, in the general equation for mass flow [eq. (4-5-1)] has been bored precisely and is thin relative to the diameter of the flow-metering section (see ASME PTC 19.5-2004, subsection 4-5 for machine tolerances). The upstream edges of the meter that are exposed to flow must be sharp. The primary element is, therefore, referred to as a thin-plate, square-edged orifice. It is the most widely used differential pressure class meter because of its low cost and high accuracy.

The temperature and pressure measurements in this section for flow-measuring devices and calculations refer to static conditions and do not require total conditions for the calculations. Total conditions are resolved in the iteration required in the flow calculations and therefore are built into the calculation procedures.

4-5.2 Location of Flow-Measuring Device and Instrumentation

The flow-measuring device shall be located in a piping arrangement following the blower system discharge. It shall be used to determine the net delivered volumetric flow rate converted to inlet conditions, which excludes losses by shaft leakage, condensation, and other normal leakage that may be inherent in the blower design. This Code measures the delivered mass flow rate corrected to the inlet density condition to equate the net inlet volumetric flow rate of the blower system between the site and shop test conditions.

Considering an orifice as a flow-metering element, the differential pressure shall be measured from static taps located in the vicinity of the orifice as indicated in Figure 4-5.5-1. The minimum length of straight pipe preceding the orifice shall follow the recommendations as provided in ASME PTC 19.5-2004, Table 7-1.2-1 (see Nonmandatory Appendix M, Table M-2-1). Temperature measurements shall be located upstream or downstream of the differential orifice as defined in para. 4-5.14. A flow conditioner shall be used in all piping configurations where the straight number of piping lengths is less than the values presented in ASME PTC 19.5-2004, 7-1.2-1 (see Table M-2-1 in Nonmandatory Appendix M), and an additional 0.5% shall be added to the uncertainty, as noted in ASME PTC 19.5-2004, Table 7-1.2-1, General Note (b). Flow conditioner shall be of tubular, crossed plates, or Étoile type to ensure uniform flow in advance of the differential fluid device. See para. 4-5.3 for guidance on flow conditioners.

4-5.3 Flow Conditioners

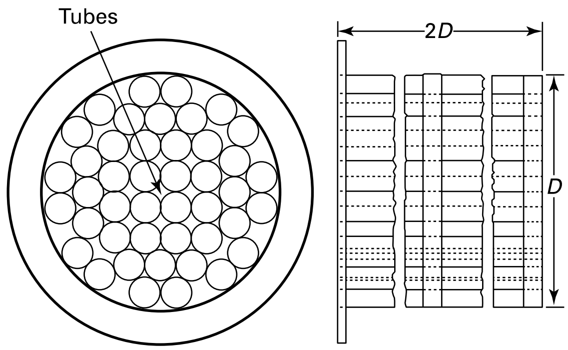
Flow conditioners shall be of the tubular, crossed-plate, or Étoile design. The following section provides guidance for the construction of these types of flow conditioning devices. The use of flow conditioners may not decrease the requirements for straight pipe and may not reduce the test uncertainty.

The recommended designs of flow conditioners are shown in Figures 4-3.5-3, 4-3.5-4, and 4-5.3-1. For both removing swirl and smoothing the velocity profile, a flow conditioner of the tube-bundle type is preferred. Tube-bundle designs [see Figure 4-5.3-1, illustration (a)] with between 19 and 41 tubes have been used successfully.

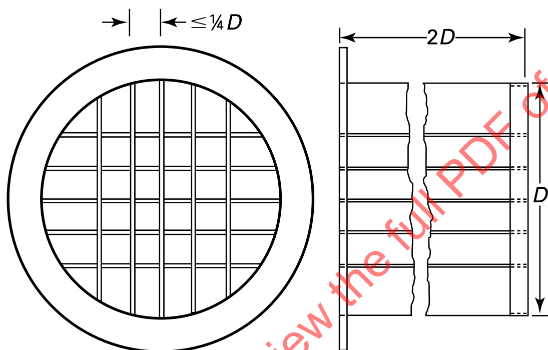
A tube bundle straightener consists of a number of parallel tubes fixed together and held rigidly in the pipe. It is important in this case that the various tubes are parallel with each other and with the pipe axis. If this requirement is not met, the straightener itself might introduce disturbances into the flow. There shall be at least 19 tubes. Their length shall be at least 20 times the tube diameter. The tubes shall be joined in a bundle and installed tangential to the pipe wall.

The use of a tubular flow conditioner with at least 19 tubes, a crossed-plate flow conditioner with the minimum number of plates [see Figure 4-5.3-1, illustration (b)], or a flow conditioner with the Étoile [see Figure 4-5.3-1, illustration (c)] is recommended for removing swirl. See Table 4-5.3-1 for the loss coefficient for each type of flow

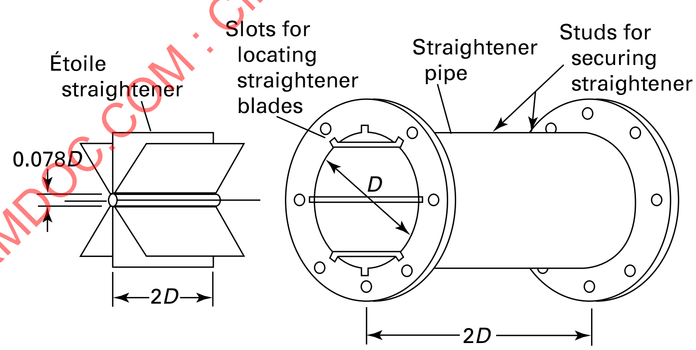
Figure 4-5.3-1 Recommended Designs of Flow Conditioner



(a) Tubular



(b) Crossed Plates



(c) Étoile

Table 4-5.3-1 Loss Coefficients for Flow Conditioners

Flow Conditioner Type	Loss Coefficient, k
Tube bundle	
41 tubes	8.0
19 tubes	5.0
Crossed plates	2.2
Étoile	1.1

GENERAL NOTE: Flow conditioner estimated loss is determined as follows:

$$\Delta p_{\text{loss}} = k\left(\frac{\rho V_1^2}{2g_c}\right)$$

where k is the multiple of the upstream dynamic pressure.

conditioner. For additional guidance on crossed-plate and Étoile flow conditioners, refer to ASME PTC 19.5-2004.

4-5.4 Metering Section Fabrication of Piping

The normal methods of fabricating piping and components are not satisfactory for accurate flow measurement. The requirements set forth below must be followed and, for satisfactory results, no deviations may be permitted. In the test lab design stages, check the installation drawing for clarity and precision of fabrication instructions.

(a) Inside pipe walls shall not be polished but should be as smooth as is commercially practical. Seamless pipe or cold-drawn seamless tubing should be used. Seamed pipe is acceptable when the seam is parallel to the flow direction and the seam follows the guidance of (b).

(b) Grooves, scoring, pits, raised ridges resulting from seams, distortion caused by welding, offsets, backing rings, and similar irregularities, regardless of size, that change the inside diameter at such points by more than $k/D < 10^{-3}$ shall not be permitted. When required, the roughness may be corrected by filling in, grinding, or filing off to obtain smoothness within.

(c) Under no circumstances shall changes of diameter (e.g., shoulders, offsets, and ridges) greater than 0.003D be permitted within 4D of the primary element. Control should be affected by valves located downstream of the primary element. Any upstream valves before the primary element shall be fully open and follow requirements of Figure 4-5.5-1 and ASME PTC 19.5-2004, Table 7-1.2-1.

4-5.5 Metering Section Piping Adjacent to the Primary Element

(a) The primary element or flow section shall be fitted between two sections of straight cylindrical pipe of constant cross-sectional area, in which there is no obstruction or branch connection (whether or not there is flow into or out of such connections during measurement) other than those specified in ASME PTC 19.5-2004, Table 7-1.2-1. The pipe is considered straight when it appears so by visual inspection. The required minimum straight lengths of pipe, which conform to the description above, vary according to the nature of the fittings, the type of primary element, and the diameter ratio. ASME PTC 19.5-2004, Table 7-1.2-1 indicates the upstream and downstream straight lengths required for installation between various fittings and the primary element.

(b) ASME PTC 19.5-2004, Table 7-1.2-1 recommends the piping installation for these meter types. For installation lengths that reside between the two listed lengths in the table, a systematic uncertainty of ±0.5% shall be added to the coefficient of discharge component. Straight lengths shorter than those given in parentheses in this table shall not be acceptable for a test.

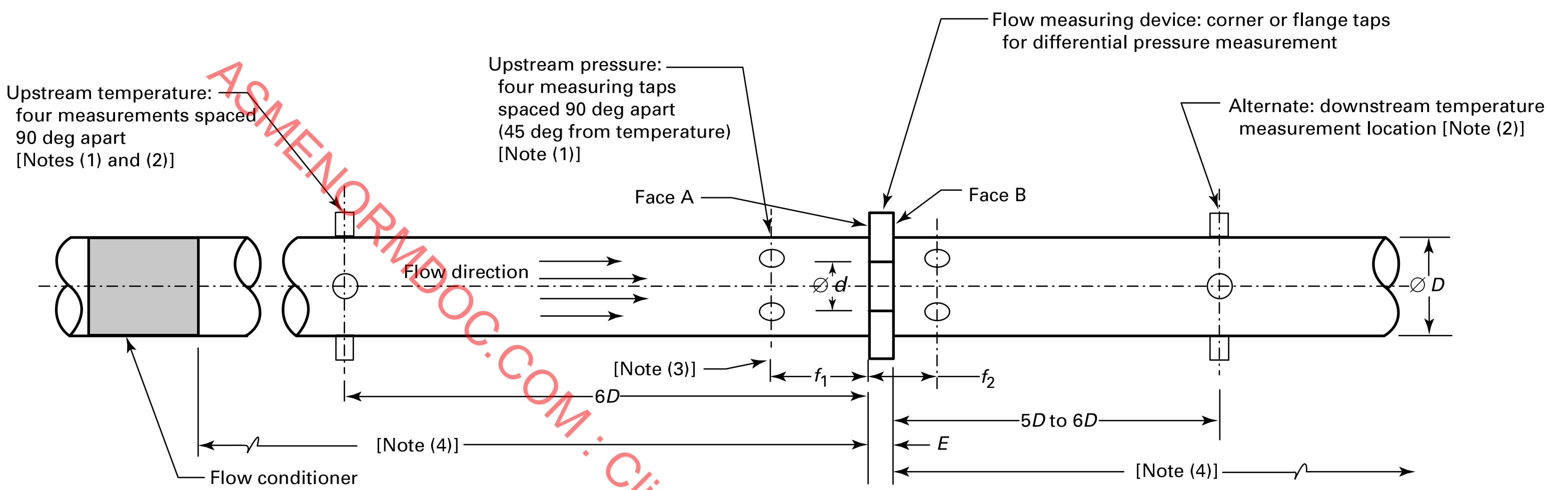
(c) The internal pipe diameter, D (refer to Figure 4-5.5-1), shall be measured on four or more diameters in the plane of the inlet pressure tap port. Check measurements shall be made on three or more diameters in two additional cross sections at least two pipe diameters from the inlet face of the orifice plate or flow nozzle, or past the weld, whichever is the greater distance. The values of all such upstream diameters shall be at maximum 0.4%. The average of all diameters near the plane of the inlet pressure tap shall be used in computing the diameter ratio of the primary element.

(d) Measurements of the diameter of the outlet section shall be made in the plane of the outlet pressure tap to ensure that the diameter of the outlet section agrees with that of the inlet section, within twice the tolerance given above for the diameters of the inlet section.

(e) Flanges, when used, shall be constructed and attached to the pipe so that there is no recess greater than $^1\!/_4$ in. (6 mm) between the primary element and the end of the pipe, measured parallel to the axis of the pipe.

(f) ASME PTC 19.5-2004, Table 7-1.2-1 summarizes the recommendations for the length of metering section to be fabricated as a function of the piping surrounding the flow measurement location. Minimum straight lengths are required between various fittings located upstream or downstream of the differential-type flow element. It is not practical to show every possible installation; for installations not covered explicitly, or where the piping configuration and fittings are not known at the time of design, the worst case shall be used (the maximum lengths of straight pipe). When more than one type of piping configuration is found upstream of the metering section, each one of which may have some effect, then the metering section shall be fabricated in accordance with the maximum lengths specified on the applicable schedules. A calibration should be performed in accordance with ASME PTC 19.5-2004, para. 7-2.4(b). The straight lengths given in ASME PTC 19.5-

Figure 4-5.5-1 Flow-Measuring Device Piping Arrangement



GENERAL NOTES:

(a) Tap shall also be known as measurement location.

(b) All dimensions shall be measured from the appropriate face of the differential device.

(c) Piping shall be insulated as in para. 4-4.6.

(d) see para. 4-5.7 for referencing dimension E, f_1, f_2.

(e) Drawing is not to scale.

NOTES:

(1) Flowmetering section: see ASME PTC 19.5-2004, Table 7-1.2-1 for required straight lengths.

(2) Differential pressure measurement by corner or flange taps, upstream or downstream (D and $D/2$ taps) are also acceptable.

(3) Pressure and temperature measurement locations shall be rotated circumferentially 45 deg in comparison to each other.

(4) Temperature measurement locations following the differential device shall be also acceptable.

Table 4-5.6-1 Values of Constants in the General Equation for Various Units

Units for Mass Flow Rate, q_m, Units	Units for Meter Geometry, d or D,	Units for Fluid Density, ρ	Units for Differential Pressure, Δp	Values of Constants	
				Proportionality Constant, g_c	Units Conversion Constant, n
$\frac{\text{kg}}{\text{sec}}$	m	$\frac{\text{kg}}{\text{m}^3}$	Pa	g_c = 1.0 dimensionless	$n = 1.0\left(\frac{\text{kg}}{\text{m}\cdot\text{sec}^2\cdot\text{Pa}}\right)^{1/2}$
$\frac{\text{lbm}}{\text{hr}}$	in.	$\frac{\text{lbm}}{\text{ft}^3}$	$\frac{\text{lbf}}{\text{in.}^2}$	$g_c = 32.1741\cdot\frac{\text{lbm}\cdot\text{ft}}{\text{lbf}\cdot\text{sec}^2}$	$n = 300.0\frac{\text{ft}^2}{\text{sec}^2}\left(\frac{\text{in.}^2\cdot\text{sec}^2}{\text{ft}^2\cdot\text{hr}^2}\right)^{1/2}$
$\frac{\text{slugs}}{\text{sec}}$	ft	$\frac{\text{slug}}{\text{ft}^3}$	$\frac{\text{lbf}}{\text{ft}^2}$	g_c = 1.0 dimensionless	$n = 1.0\left(\frac{\text{slug}\cdot\text{ft}}{\text{lbf}\cdot\text{sec}^2}\right)^{1/2}$

2004, Table 7-1.2-1 are minimum values, and straight lengths longer than those indicated are always recommended.

(g) If the upstream piping configuration is more complicated than as listed, see ASME PTC 19.5-2004.

(h) In the case of venturis, if one of the minimum straight lengths adopted is between the values listed in ASME PTC 19.5-2004, Table 7-1.2-2 and ±0.5%, additional uncertainty shall be applied to the flow coefficient uncertainty.

4-5.6 General Equation for Mass Flow Rate Through a Differential Pressure Class Meter

Formulas for calculating mass flow for a variety of flow-measuring devices as provided in ASME PTC 19.5-2004 shall be used. Methods are included for the determination of the discharge coefficient, fluid expansion factor, and metering element thermal expansion coefficient for various flow elements. Nomenclature and symbols follow ASME PTC 19.5-2004. All pressures are static and not total.

(a) The general equation for mass flow is

$$q_m = n\frac{\pi}{4}d^2 C_d \varepsilon_1 \sqrt{\frac{2\rho_1(\Delta p)g_c}{1-\beta^4}} \tag{4-5-1}$$

Equation 4-5-1 is applied to flow calculations for all orifices and nozzles, and is valid both for liquids and for gases flowing at subsonic velocity. Density shall be based on static measurements. This Code is focused primarily on airflow and utilizing orifices for volumetric flow rate measurement. If nozzles are utilized for volumetric flow rate measurement, then refer to ASME PTC 19.5-2004.

(b) Values of n and g_c for commonly used combinations of units are shown in Table 4-5.6-1. Use of other units for any parameter(s) in the general equation is permissible, provided the n factor is correctly determined.

4-5.6.1 Calculation of Expansion Factor, ε_1

(a) For orifices, abrupt radial as well as axial expansions take place, and the analytical derivation of eq. (4-5-3) is invalid. It has been determined that the product of C_d and ε_1 for subsonic flow orifices depends on *Re* and the acoustic ratio, $\Delta p/\kappa p_1$. Based on the data, if ρ_1 is the value of density upstream of the fluid meter used for the flow calculation, then

$$\varepsilon_1 = 1 - \left[0.41 + 0.35\left(\beta_{exp}\right)^4\right]\frac{\Delta p}{\kappa p_1} \tag{4-5-2}$$

(b) The expansion factor for nozzles, with density determined at the upstream pressure tap, has been derived

$$\varepsilon_1 = \left\{ r^{2/\kappa}\left[\frac{\kappa}{\kappa-1}\right]\left[\frac{1-r^{\frac{(\kappa-1)}{\kappa}}}{1-r}\right]\cdot\left[\frac{1-\left(\beta_{exp}\right)^4}{1-\left(\beta_{exp}\right)^4 r^{2/\kappa}}\right]\right\}^{1/2} \tag{4-5-3}$$

where r is defined as

$$r = \left(\frac{p_2}{p_1}\right) = \left(\frac{p_1-\Delta p}{p_1}\right) \tag{4-5-4}$$

Equation (4-5-4) is valid for any gas or vapor for which κ is known.

(c) Equations (4-5-2) and (4-5-3) are valid only for cases where $p_2/p_1 \geq 0.8$. Differential pressure meters must not be sized for compressible fluids such that the pressure ratio is lower than 0.8 to avoid Mach number effects. Therefore, the ratio of the flowmeter differential pressure to the pressure measurement upstream of the flow element shall be in the following range:

$$0.0 \leq \left(\frac{\Delta p}{p_1}\right) \leq 0.2 \qquad (4\text{-}5\text{-}5)$$

(d) Temperature can be measured downstream of the meter to avoid disturbing the flow profile. Static pressure shall be measured at the upstream tap. Temperature at the upstream tap, T_1, can be calculated assuming the ideal gas relation using eq. (4-5-6) and the relationship $\Delta p = p_1 - p_2$ when the piping and flange locations in the flow-metering section are insulated as per para. 4-4.6.

$$T_2 = T_1\left[\frac{p_2}{p_1}\right]^{(\kappa-1)/\kappa} = T_1\left[1 - \frac{\Delta p}{p_1}\right]^{(\kappa-1)/\kappa} \qquad (4\text{-}5\text{-}6)$$

4-5.7 Empirical Formulations for Discharge Coefficient, C_d

The empirical formulation for the discharge coefficient for orifices is given by the following equation:

$$C_d = 0.5959 + 0.0312\left(\beta_{exp}\right)^{2.1} - 0.1840\left(\beta_{exp}\right)^{8} + \frac{0.0900L_1\left(\beta_{exp}\right)^4}{\left[1-\left(\beta_{exp}\right)^4\right]} - 0.0337L'_2\left(\beta_{exp}\right)^3 + \frac{91.71\left(\beta_{exp}\right)^{2.5}}{R_e^{0.75}} \qquad (4\text{-}5\text{-}7)$$

where

E = orifice plate thickness
L_1 = dimensionless correction for upstream tap location
= l_1/D, measured from upstream Face A
l_1 = distance from upstream face of orifice plate to upstream pressure tap
L'_2 = dimensionless correction for downstream tap location
= $(l_2 - E)/D$, measured from downstream Face B
l_2 = distance from upstream face of orifice plate to downstream pressure tap

Refer to ASME PTC 19.5-2004, Figure 4-2-1.

4-5.8 Thermal Expansion/Contraction of Pipe and Primary Element

In actual flow conditions, both d and D change from the measured values in the factory or laboratory because of thermal expansion or contraction. This occurs when the flowing fluid is at a different temperature than that at which the primary element and the pipe were measured, and if the pipe and element are of different materials or originally calibrated at different temperatures for each.

$$d_{exp} = d_{meas} + \alpha_{element}d_{meas}(T - T_{meas}) \qquad (4\text{-}5\text{-}8)$$

$$D_{exp} = D_{meas} + \alpha_{pipe}D_{meas}(T - T_{meas}) \qquad (4\text{-}5\text{-}9)$$

$$\beta_{exp} = \frac{d_{exp}}{D_{exp}} \qquad (4\text{-}5\text{-}10)$$

4-5.9 Procedure for Sizing a Differential Pressure Class Meter and Selection

The user must be careful when sizing a differential pressure class meter that the calculated β_{exp}, d, Reynolds number, and r_p as measured across the element are within the specified ranges for each meter. The resolution of measurements from instrumentation shall follow that as described in Section 4. If any limitations are exceeded, then either a different size of the same meter type (d, D, or both) shall be used or a different type of differential pressure class meter should be evaluated for the application. The metering section, arrangement, and length dimensions shall be per para. 4-5.5.

Differential class meters have a limited range for operation. In selecting and sizing a meter, care shall be taken to stay within the limitations of the meter, piping arrangement, instrumentation, and gas and thermodynamic properties.

If the chosen value of differential pressure for the design or expected flow rate in the sizing of an orifice results in a calculated β_{exp} that exceeds the prescribed limits, it may be necessary to use a flow nozzle or venturi. Both devices have a higher flow measurement capacity in comparison to orifice devices for the same size beta ratio. For reference, discharge coefficients for nozzles and venturi-metering runs are in the order of 1.0 compared to typical discharge coefficients of orifices in the order of 0.6. The discharge coefficient shall be determined as described herein.

4-5.10 Restrictions of Use

The following restrictions must be met for proper use of these meters:

(a) The flowmeter, flow section, pressure taps, and connecting tubing shall be manufactured, installed, and used in strict accordance with the specifications herein.

(b) The flow shall be steady or changing very slowly as a function of time. Pulsations in the flow shall be small compared with the total flow rate. The frequency of data collection shall adequately cover several periods of unsteady flow. Refer to ASME 19.5-2004, Section 6 for additional guidance regarding pulsating flow.

4-5.11 Flow Calculation Procedure

(a) Equation (4-5-1) shall be used for all differential pressure class meters and is valid for subsonic airflow measurement.

(b) Used for airflow, ε_1 is given by eq. (4-5-2) for orifices.

(c) Per para. 4-5.8, d and D shall be corrected to the fluid temperature of the measurement.

(d) The applicable air density shall be determined from static pressure and static temperature measurements.

(e) All quantities in the general eq. (4-5-1), except the discharge coefficient, are known once steps 4-5.6.1(b) through 4-5.6.1(d) have been completed. Because C_d depends on Reynolds number, which itself depends on flow rate, eq. (4-5-1) is now solved by iteration. It is convenient to initially guess a discharge coefficient of $C_d = 0.6$ for orifices. A reiteration is begun using the new value of the discharge coefficient as calculated from the new Reynolds number from the previous iteration.

(f) This process shall be continued until the difference between successive calculated flow rates is less than 0.003%. It is also convenient to simply iterate until convergence to five significant digits is achieved. Convergence is generally achieved with four iterations.

4-5.12 Introduction to Orifice Meters

4-5.12.1 Types of Thin-Plate, Square-Edged Orifices. Thin-plate, square-edged orifices are classified based on the locations of their differential pressure taps. The three types of tap geometries recommended by this Code for primary data when conducting ASME performance tests in accordance with a code are

(a) flange taps

(b) D and $D/2$ taps

(c) corner taps

Pressure-tap locations for flange taps and D and $D/2$ taps shall be given by the measured distance from the centerline of the pressure tap to the upstream Face A or to the downstream Face B of the orifice plate, as seen in Figure 4-5.5-1. The thickness of the gaskets or other sealing material is included in the given dimension.

4-5.12.2 Multiple Sets of Differential Pressure Taps. Four pairs of differential pressure taps shall be required (see Figure 4-5.5-1). Differential pressure taps are separated by 90 deg circumferentially.

Orifice degradation through use, dirt, or other irregularities can go unnoticed if only one set of taps is used. Differential pressure shall be measured at each set of taps. The flow calculation shall be done separately for each pair and averaged. Investigation shall be required if the results differ from each tap set calculation by more than the flow measurement uncertainty.

4-5.12.3 Deflection and the Required Thickness, *E*, of Orifice Plate. Deflection of the orifice plate during flowing conditions is unavoidable (Figure 4-5.12.3-1), but shall be small enough so that the total deflection, τ, is less than $0.005(D - d)/2$ (assuming the plate was perfectly flat with zero differential pressure applied). Reference ASME 19.5-2004, Table 4-5.1 to review minimum orifice plate thickness, E, for stainless steel orifice plates.

4-5.12.4 Upstream Face A. With zero differential pressure applied, the plate upstream Face A shall be flat within $0.01(D - d)/2$. The orifice plate mounting shall have no significant distorting effect on the plate.

The upstream Face A shall have a maximum roughness of no greater than 5 µin. (0.13 µm) within a circle whose diameter is not less than D and is concentric with the bore.

The lip-like upstream side of the orifice plate that extends out of the pipe and is called the tag shall be permanently marked with identification of the upstream side, measured bore diameter, orifice identifying number, plate thickness and angle of bevel, even if zero.

4-5.12.5 Beta Ratio Recommendation (Orifice Diameter). The inner diameter of the differential device, d, shall be such that $0.20 < \beta_{exp} < 0.75$; however, it is recommended that a β_{exp} of 0.70 not be exceeded. Refer to ASME PTC 19.5-2004, Table 7-1.2-1 for additional guidance.

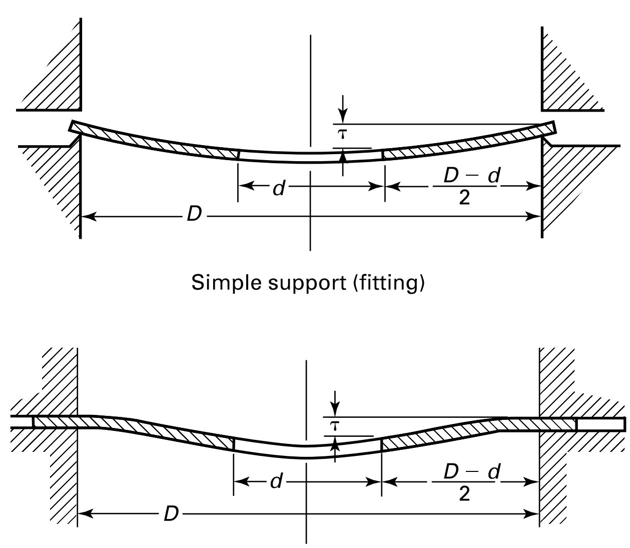
Where the beta ratio is defined as the ratio of the inner diameter of the differential device, d, divided by the inner diameter, D, piping wall of the fluid metering section

$$\beta = \frac{d}{D} \tag{4-5-11}$$

and noting eq. (4-5-10), considering the thermal expansion of materials becomes therefore

$$\beta_{exp} = \frac{d_{exp}}{D_{exp}}$$

Figure 4-5.12.3-1 Deflection of an Orifice Plate by Differential Pressure



4-5.12.6 Eccentricity of Orifice in Metering Section. An orifice plate shall be perpendicular to the centerline of the metering run within 1 deg. The manufacturing and installation requirements needed to comply with these restrictions are addressed in ASME PTC 19.5.

4-5.13 Machining Tolerances and Dimensions for Differential Pressure Taps

4-5.13.1 Orifice-Metering Runs: Shape, Diameter, and Angular Position. The centerline of the taps shall meet the pipe centerline and be at right angles to it within ±2 deg. At the point of breakthrough, the hole shall be circular.

The edges shall be flush with the internal surface of the pipe wall and shall be as sharp as can be reasonably manufactured. Because of the criticality of eliminating burrs or wire wedges at the inner edge, rounding is permitted but it should be minimized. The radius caused by rounding shall not exceed 0.0625d. Visually, no irregularities should appear inside the connecting hole, on the edges of the hole drilled in the pipe wall, or in the pipe wall close to the pressure tap.

The maximum allowable diameters of the tap holes through the pipe wall or flange are provided in para. 4-3.8, or can be referenced from ASME PTC 19.5. Interpolation for intermediate sizes is permitted. Upstream and downstream tap holes shall be the same diameter. The minimum size of the tap holes is 0.25 in. (6 mm).

The pressure tap holes shall be circular and cylindrical. They should be constructed such that they may abruptly increase in diameter at any location away from the inner wall.

4-5.13.2 Orifice Tap Metering Runs. The spacing, l, of a pressure tap is the distance between the centerline of the pressure tap and the plane of one specified face of the orifice plate. When installing the pressure taps, take into account the thickness of the gaskets and/or sealing material that is used.

(a) Spacing of Flange Taps. The center of the tap for p_1 is l_1 = 1.00 in. (25.4 mm) measured from the upstream Face A of the orifice plate. The center of the tap for p_2 is l_2 = 1.00 in. (25.4 mm) measured from the downstream Face B of the orifice plate. Manufacturing tolerances for flange tap locations are shown in ASME PTC 19.5-2004, Figure 4-2.1.

(b) Spacing of D and D/2 Taps. The center of the tap for p_1 is $l_1 = D \pm 5\%$ from the upstream Face A of the orifice plate. The center of the tap for p_2 is l_2= 1.00 in. (25.4 mm) measured from the downstream Face B of the orifice plate. Manufacturing tolerances for D and $D/2$ taps locations are shown in of ASME PTC 19.5-2004, Figure 4-2.1.

(c) Corner tap orifice metering runs are allowable, and shall follow the proper guidance of ASME PTC 19.5-2004.

4-5.14 Location of Temperature and Static Pressure Measurements

The general equation for mass flow [eq. (4-5-1)] was developed to calculate the velocity at the throat of the device. Thus, temperature and static pressure measurements for density and viscosity determination shall preferably be determined at the upstream side of the orifice. However, temperature measurement upstream can interfere with the flow pattern, thus the temperature thermowells can be located between 5D and 6D downstream of the orifice Face B.

For air, with the requirement that $p_2/p_1 > 0.80$, the upstream temperature may be determined assuming isentropic expansion of the fluid across the orifice.

4-5.15 Piping and Test Arrangement

Pipe configurations used for performance testing blowers is the key ingredient to achieving good test results. Incorrect dimensions, air leaks, poor surface preparation, and many other variables can lead to inaccurate test readings. Once the air is discharged from the blower, the piping shall be responsible for simulating the characteristics that the air will experience when the blower is installed on-site (pressure, temperature, flow).

(a) Discharge Piping

The blower discharge piping is composed of three main sections: the pre-metering section, the metering section, and the post-metering section. The metering section, being the most important, shall follow straight run requirements. Other components of the metering section include the metering device, flow conditioner (optional), throttling device, and instrumentation. The pre-metering section contains the discharge flange, pressure taps, temperature taps, and any piping bends that precede the straight run (metering section). The post-metering section contains the remaining piping required to expel the test air in the proper location. In some cases, the manufacturer may choose to install a silencer on piping. No measurement instrumentation is required in this section. The guidelines in subsection 4-5 shall be followed to ensure that the metering section is capable of accurately measuring airflow.

Straight lengths for pipe sections containing a flow orifice shall meet the recommended dimensions as stated in ASME PTC 19.5-2004, Table 7-1.2-1. For instances where the straight length is not feasible, the difference in length may be within 10% of the required length if this discrepancy is agreed upon by both parties.

4-6 RELATIVE HUMIDITY

The instruments shall be located at the air source for the test. The instruments shall be protected from weather, direct sunlight, and fluctuating temperature changes. The relative humidity shall be measured in the vicinity of the inlet temperature instrument location in an area of relatively low velocity (less than 500 ft/min), such that the relative humidity and temperature measurements are considered from the same air source and that the water vapor fraction thereby calculated is representative of the inlet source. If it is believed that the inlet temperature is different than the temperature at the point of relative humidity measurement while vapor fraction is unchanged, then a separate measurement of temperature shall be taken with the relative humidity measurement in order to determine the vapor fraction of the inlet air.

4-7 SPEED MEASUREMENT

Blower rotational speed shall be measured with instrumentation having an accuracy greater than or equal to 0.15%. Frequency measurement via, for example, power analyzer, magnetic pickup, or laser strobe can be used following the accuracy defined herein.

Section 5
Computation of Results

5-1 INTRODUCTION

5-1.1 The Calculation Procedure

The process of establishing blower performance from test data involves a number of calculation steps for all blower types, including positive displacement and dynamic. This Section provides the calculation structure for the differing blower types and details the suitable common calculations for air as the compressible fluid. In chronological order, the steps are as follows:

(a) Process the raw test data.

(b) Compute inlet air conditions.

(c) Select suitable performance calculation methodology based on compression technology (see Figure 5-1.1-1).

(d) Calculate test performance.

5-1.2 Fluctuations

Three or more sets of readings shall be used and averaged to obtain the test point. The allowable fluctuation between sets of readings is shown in Table 3-5.5-1. The fluctuation shall be computed by taking the difference of the highest reading and the lowest reading and dividing by the average of all the readings.

$$\Delta F = \frac{100(A_H - A_L)}{\frac{1}{n}\sum_{i=1}^{n} A_i} \quad (5\text{-}1\text{-}1)$$

where

A_H = highest reading
A_i = ith reading, value at current iteration
A_L = lowest reading
ΔF = fluctuation expressed in % (see Table 3-5.5-1)
i = iteration number
n = total number of readings

If the fluctuation values of Table 3-5.5-1 are satisfied, then the point shall be assumed to be valid.

5-1.2.1 Test Point Data. The individual readings shall be summed and divided by the total number of readings to establish an average. This average shall be used as the test point data.

5-1.3 Total Pressure and Temperature Conditions

Gas state static test point data shall be converted to total condition values for the computational procedure. This does not preclude final presentation in terms of static conditions, but total values are used in the intermediate calculations.

The relationship between static and total properties is velocity dependent. Average total properties shall be estimated herein from the average velocity at the measurement station.

The average velocity at the measurement station is given by

$$V = \frac{q_m}{\rho_{\text{static}} A} \quad (5\text{-}1\text{-}2)$$

Simplified methods for converting between static and total conditions at low fluid Mach numbers shall be presented in the following paragraphs.

5-1.4 Test Pressure

For measurement station fluid Mach numbers of 0.2 or less, the effects of compressibility are small. A good approximation of velocity pressure may be obtained by assuming incompressible flow at the measurement station and calculating an approximate density from the measured static pressure and measured temperature.

$$\rho_{\text{static}} = \frac{p_{\text{static}}}{R_g T_{\text{meas}}} \quad (5\text{-}1\text{-}3)$$

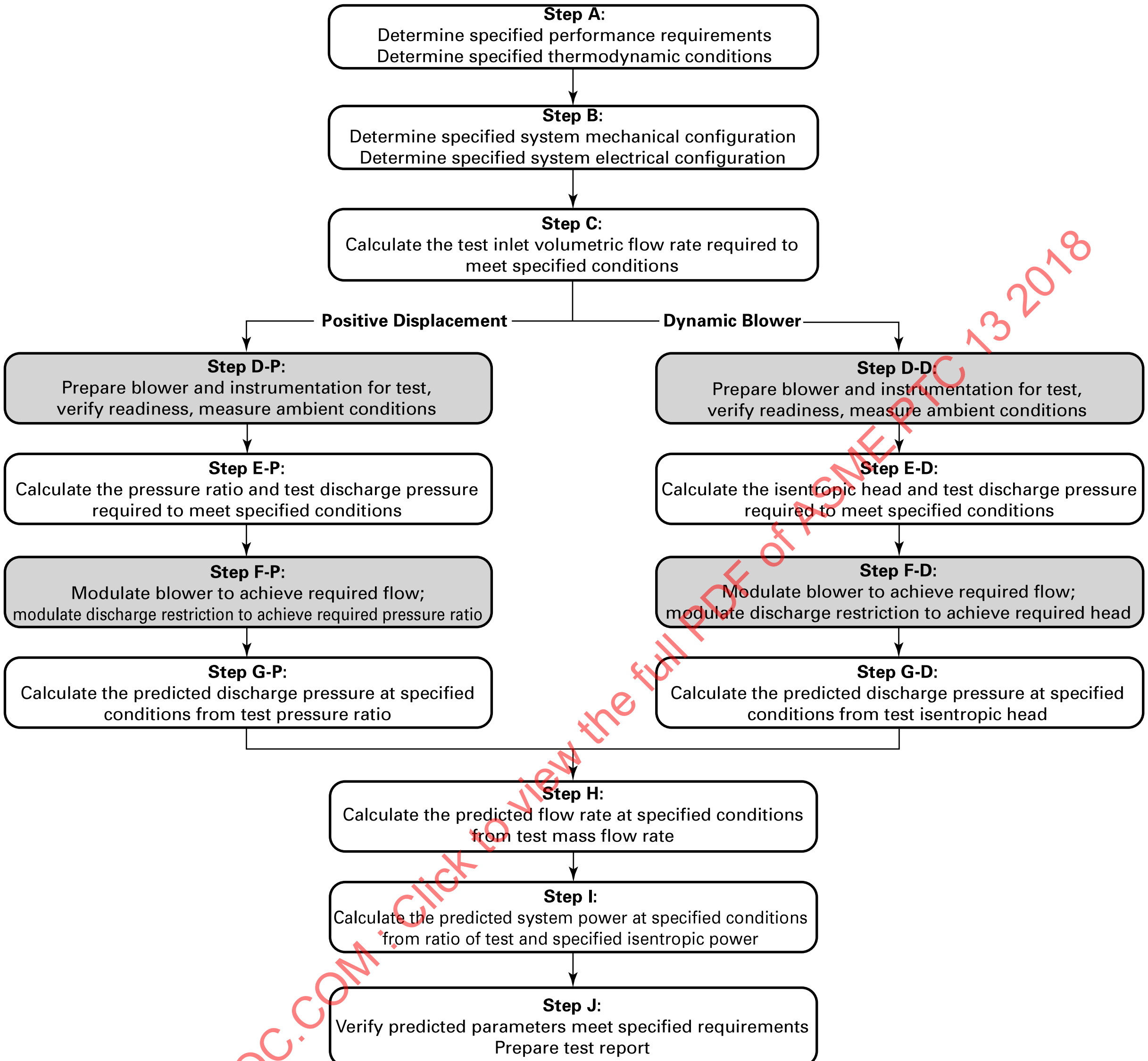
$$V_{av} = \frac{q_m}{\rho_{\text{static}} A} \quad (5\text{-}1\text{-}4)$$

$$p = p_{\text{static}} + \frac{\rho V_{av}^2}{2 g_c} \quad (5\text{-}1\text{-}5)$$

5-1.5 Test Temperature: Recovery Factor

The temperature indicated by a sensing element is normally a value somewhere between the static and total temperature, depending upon the ability of the sensor to recover the converted kinetic energy of the gas stream. This ability is defined in terms of a recovery factor.

Figure 5-1.1-1 Calculation Methodology Framework



$$r_f = \frac{T_{\text{meas}} - T_{\text{static}}}{T - T_{\text{static}}} \tag{5-1-6}$$

The recovery factor is primarily dependent upon geometric configuration, orientation, and fluid Mach number. Standardized performance test code wells (refer to ASME PTC 19.3) used at velocities below 300 ft/sec have a recovery factor for air equal to 0.65. Recovery factors for various sensors may be available from the instrument manufacturer.

The test total temperature shall be calculated from the measured temperature taking into account the effect of recovery factor.

The difference between total and static temperatures should be evaluated from the following equation considering the c_p at the blower inlet condition (this applies to discharge total and static temperatures also):

$$T - T_{\text{static}} = \frac{V_{av}^2}{(2Jg_c c_p)} \tag{5-1-7}$$

This equation is accurate for ideal gases (using an inlet c_p). It is less accurate for fluid Mach numbers above 0.2.

The above equation and the definition of recovery factor r_f shall combine to give:

$$T = T_{\text{static}} + (1 - r_f)\left(\frac{V_{av}^2}{(2Jg_c c_p)}\right) \quad (5\text{-}1\text{-}8)$$

See Nonmandatory Appendix G for further information regarding appropriate use of the mechanical equivalent of heat, J, and g_c.

5-1.6 Test Density

The test total density shall be calculated from the test total pressure and total temperature as

$$\rho_{\text{tot}} = \left(\frac{p_{\text{tot}}}{R \cdot T_{\text{tot}}}\right) \quad (5\text{-}1\text{-}9)$$

NOTE: It is important to reflect dimensionally consistent units in calculations throughout this Performance Test Code.

5-1.7 Speed Irregularity

As with fluctuations, the speed irregularity shall be maintained during a test point as defined below within a range of −0% to 1%. This is computed by taking the minimum and maximum speeds during an operating test point collection and dividing by the average of said speeds. See Table 3-5.5-1.

$$N_r = \frac{N_{\max} - N_{\min}}{\left(\frac{N_{\max} + N_{\min}}{2}\right)} \quad (5\text{-}1\text{-}10)$$

In many cases, the nominal frequency of the utility power source will differ from the specified power frequency, which will affect the operating speed of the blower system. The use of a shop variable frequency drive or a generator to obtain the specified frequency, typically 50.0 Hz or 60.0 Hz, is permissible so long as the fluctuation and deviation are within the limits identified in Table 3-5.5-1 and subsection 4-2.

5-1.8 Inlet Volumetric Flow Rate Definition

This Code uses a volumetric flow rate definition in the calculation process that has the units of volumetric flow rate

$$q_{v,i} = \frac{q_{m,d}}{\rho_{\text{tot},i}} \quad (5\text{-}1\text{-}11)$$

where

$q_{m,d}$ = delivered mass flow rate
$\rho_{\text{tot},i}$ = total inlet density

This definition is consistent with the use of total properties in the calculation procedure. It does not represent the actual local volumetric flow rate because it is based upon total rather than static density. All references to calculated volumetric flow rate shall imply this definition unless otherwise stated. This is the blower package inlet volumetric flow rate.

If the performance is specified as mass flow rate and discharge pressure at specific inlet conditions, then the corresponding inlet volumetric flow rate can be calculated. This will be the test volumetric flow rate. Note that relative humidity must be included in the calculation.

5-2 COMPUTATIONAL METHODS FOR IDEAL GASES

The thermodynamic properties of air shall be determined for the test and specified inlet air conditions by using the equations detailed herein.

The saturated vapor pressure may be determined by referring to the saturation line of the ASME Steam Tables, or by directly solving for the thermodynamic saturation pressure through the implicit quadratic equation supplied therein.

Similarly, the following empirical equation may be used to determine the saturated vapor pressure with similar accuracy in comparison to the steam tables for the temperature range of 32.02°F to 130°F.

$$p_{sv}\,(\text{psia}) = 2349.081 \cdot 10^3 e^{(\beta_{sv})} \quad (5\text{-}2\text{-}1)$$

where the temperature coefficient, β_{sv}, is

$$\beta_{sv} = \frac{-7202.2367}{T(°\text{R}) - 70.431} \quad (5\text{-}2\text{-}2)$$

5-2.1 Water Vapor and Air Components

5-2.1.1 Water Vapor. The water vapor pressure of the inlet air is

$$p_{vp} = \text{RH} \cdot p_{sv} \quad (5\text{-}2\text{-}3)$$

$$HR_{\text{mix}} = \left(\frac{\text{MW}_{vp}}{\text{MW}_{da}}\right) \cdot \frac{p_{vp}}{p_a - p_{vp}} \quad (5\text{-}2\text{-}4)$$

$$x_{vp} = \frac{p_{vp}}{p_a} \quad (5\text{-}2\text{-}5)$$

$$R_{\text{mix}} = \frac{\overline{R}}{\text{MW}_{\text{mix}}} \quad (5\text{-}2\text{-}6)$$

Refer to Nonmandatory Appendix H for additional information.

5-2.1.2 Molecular Weight. The mole weight of the mixture of dry air (da) and water vapor (vp) is defined as

$$\text{MW}_{\text{mix}} = (1 - x_{vp})\text{MW}_{da} + x_{vp}\text{MW}_{vp} \quad (5\text{-}2\text{-}7)$$

where

$$MW_{da} = 28.970 \frac{\text{lbm}}{\text{lbmol}}$$

$$MW_{vp} = 18.015 \frac{\text{lbm}}{\text{lbmol}}$$

5-2.1.3 Air Density. The air density for a given condition (i) is defined as

$$\rho_i = \frac{p_i}{R_{\text{mix},i} T_i} \quad (5\text{-}2\text{-}8)$$

5-2.1.4 Absolute Fluid Viscosity. The absolute viscosity is calculated from the absolute inlet temperature (°R). The absolute fluid viscosity of air is calculated as

$$\mu_{da} = \left\{ -9.5472 \cdot 10^{-7} \left[T_i(°\text{R}) \right]^2 + 0.0063768 \left[T_i(°\text{R}) \right] + 0.6702 \right\} \cdot 10^{-7} \left(\frac{\text{lbf} \cdot \text{sec}}{\text{ft}^2} \right) \quad (5\text{-}2\text{-}9)$$

The absolute fluid viscosity of water vapor is calculated as

$$\mu_{vp} = \left\{ 1.0129 \cdot 10^{-6} \left[T_i(°\text{R}) \right]^2 + 0.0028789 \left[T_i(°\text{R}) \right] + 0.08873 \right\} \cdot 10^{-7} \left(\frac{\text{lbf} \cdot \text{sec}}{\text{ft}^2} \right) \quad (5\text{-}2\text{-}10)$$

The absolute viscosity of a mixture of air and water vapor is calculated as

$$\mu_{\text{mix}} = \frac{\mu_{da}(1 - x_{vp})\sqrt{MW_{da}} + \mu_{vp}(x_{vp})\sqrt{MW_{vp}}}{(1 - x_{vp})\sqrt{MW_{da}} + (x_{vp})\sqrt{MW_{vp}}} \quad (5\text{-}2\text{-}11)$$

5-2.2 Conversion From Standard Condition to Site-Actual Volumetric Flow Rate

The following equation converts a standard volumetric flow rate (i.e., SCFM) into a site-actual volumetric flow rate (i.e., acfm), to equate the volumetric flow rate of dry air between the standard and site actual conditions. In some cases, the actual volumetric flow rate refers to ambient conditions.

$$q_{v,a,sp} = q_{v,\text{std}} \frac{(p_a - p_{vp})_{\text{std}}}{(p_a - p_{vp})_{sp}} \left(\frac{T_{sp}}{T_{\text{std}}} \right) \quad (5\text{-}2\text{-}12)$$

where the pressure and temperature units reference absolute conditions.

To calculate the volumetric flow rate into the blower considering the sum of pressure losses of the inlet system from ducting, filtration, etc., the actual volumetric flow rate shall be converted to the inlet volumetric flow rate (e.g., icfm) as follows:

$$q_{v,i,sp} = q_{v,a,sp} \frac{(p_a)_{sp}}{(p_i)_{sp}} = q_{v,a,sp} \frac{(p_a)_{sp}}{(p_a - \Delta p_1 - \Delta p_2 \ldots - \Delta p_n)_{sp}} \quad (5\text{-}2\text{-}13)$$

5-2.3 Specific Heat of Constant Pressure and Ratio of Specific Heats

With the absolute temperature used here as Rankine (°R), the specific heat of dry air will be calculated as follows considering mole basis, and considered at the inlet condition:

$$\bar{c}_{p,da} = [3.647458 - 7.08954 \cdot 10^{-4}(T) + 9.41274 \cdot 10^{-7}(T^2) - 2.54339 \cdot 10^{-10}(T^3)] \cdot \bar{R} \quad (5\text{-}2\text{-}14)$$

$$\bar{c}_{p,vp} = [4.05380 - 5.1711 \cdot 10^{-4}(T) + 1.05975 \cdot 10^{-6}(T^2) - 2.92781 \cdot 10^{-10}(T^3)] \cdot \bar{R} \quad (5\text{-}2\text{-}15)$$

where the universal gas constant is used as

$$\bar{R} = 1.98588 \frac{\text{Btu}}{\text{lbmol} \cdot °R}$$

The molar specific heat of the mixture shall be calculated from the individual components as follows:

$$c_{p,\text{mix}} = \frac{\sum x_{vp}\bar{c}_p}{MW_{\text{mix}}} = \frac{(1 - x_{vp})\bar{c}_{p,da} + x_{vp}\bar{c}_{p,vp}}{MW_{\text{mix}}} \quad (5\text{-}2\text{-}16)$$

Performance calculations shall use the equations above.

The mixture-specific heat at inlet conditions shall be used for determining isentropic power and work per unit mass for specified and test conditions.

$$\kappa_{\text{mix},i} = \kappa_i \quad (5\text{-}2\text{-}17)$$

The ratio of specific heats referencing the temperature condition of the mixture specific heats is

$$\kappa_{\text{mix}} = \frac{c_{p,\text{mix}}}{c_{p,\text{mix}} - R_{\text{mix}}} \quad (5\text{-}2\text{-}18)$$

Refer to Nonmandatory Appendix H for additional information. Performance calculations shall use the equations above.

5-2.4 Calculating Predicted Power

The thermodynamic properties of air shall be calculated for test conditions based on the measured absolute temperature of the inlet air.

Based on the value of κ, the isentropic power of compression corresponding to test and specified conditions should be calculated

$$P_s = q_v \cdot \rho_i \cdot \left(\frac{\kappa_{mix}}{\kappa_{mix} - 1}\right) \cdot R_{mix} \cdot T_i \cdot \left[r_p^{\frac{\kappa_{mix}-1}{\kappa_{mix}}} - 1\right] \quad (5\text{-}2\text{-}19)$$

The values of all parameters should be based on the test measurements for power calculations at test conditions. The values of all parameters should be at specified values for power calculations at specified conditions.

Extrapolation from test to specified conditions should be made by calculating the power of compression for both conditions from thermodynamic equations, and then applying the ratio of these two powers to the measured total system test power

$$P_{pr} = P_t \cdot \frac{P_{s,\,sp}}{P_{s,t}} \quad (5\text{-}2\text{-}20)$$

5-3 DYNAMIC BLOWERS

Correcting the process values of the performance test for a dynamic blower is detailed below. Figure 5-1.1-1 details the flow of calculations for the procedure to detail the conditions and order of the calculation methods.

5-3.1 Specific Volume Ratio

The specific volume is defined as

$$v = \frac{1}{\rho} \quad (5\text{-}3\text{-}1)$$

The specific volume ratio is the ratio of inlet to discharge total specific volume.

$$r_v = v_i / v_d \quad (5\text{-}3\text{-}2)$$

Therefore, considering eq. (5-3-1):

$$r_v = \rho_d / \rho_i \quad (5\text{-}3\text{-}3)$$

The discharge temperature at specified conditions is required for calculating the discharge density at specified conditions. The discharge temperature should be estimated using the temperatures measured at test.

$$T_{d,pr} = T_{i,sp} \cdot \left\{ \frac{\left[\left(\frac{p_{d,sp}}{p_{i,sp}}\right)^{\frac{\kappa_{mix,sp}-1}{\kappa_{mix,sp}}} - 1\right] \cdot \left(\frac{T_{d,t}}{T_{i,t}} - 1\right)}{\left(\frac{p_{d,t}}{p_{i,t}}\right)^{\frac{\kappa_{mix,t}-1}{\kappa_{mix,t}}} - 1} + 1 \right\} \quad (5\text{-}3\text{-}4)$$

5-3.2 Isentropic Compression Work per Unit Mass (Isentropic Head)

The isentropic compression work per unit mass (isentropic head) is

$$W_s = \frac{\kappa_{mix}}{\kappa_{mix} - 1} \cdot \frac{\overline{R}}{MW_{mix}} \cdot T_i \cdot \left(r_p^{\frac{\kappa_{mix}-1}{\kappa_{mix}}} - 1\right) \quad (5\text{-}3\text{-}5)$$

Package pressure ratio

$$r_p = \frac{p_d}{p_i} \quad (5\text{-}3\text{-}6)$$

5-3.3 Dynamic Blower Power Prediction: Test Flow/Speed Matching Specified Flow/Speed

5-3.3.1 Test Flow/Speed Matching Specified Flow/Speed. The inlet volumetric flow rate at specified conditions ($q_{v,sp}$) is defined with eq. (5-2-13) for the specified conditions. The inlet volumetric flow rate defined with eq. (5-2-13) shall be established as the test inlet volumetric flow rate.

Inlet volumetric flow rate

$$q_{v,sp} = q_{v,t} \quad (5\text{-}3\text{-}7)$$

The isentropic head at specified conditions ($W_{s,sp}$) is defined with eq. (5-3-5) for the specified conditions. The isentropic head as defined in eq. (5-3-5) shall be established as the test isentropic head.

Isentropic head

$$W_{s,sp} = W_{s,t} \quad (5\text{-}3\text{-}8)$$

Extrapolation from test wire power to predicted wire power at specified conditions shall therefore be calculated through the ratio of test to specified conditions of the inlet density, inlet volumetric flow rate, and isentropic head through the following equation for predicted power (P_{pr}):

$$P_{pr} = P_t \cdot \left(\frac{\rho_{sp,i}}{\rho_{t,i}}\right) \cdot \left(\frac{q_{v,sp}}{q_{v,t}}\right) \cdot \left(\frac{W_{s,sp}}{W_{s,t}}\right) \quad (5\text{-}3\text{-}9a)$$

Alternatively

$$P_{pr} = P_t \cdot \left(\frac{\rho_{sp,i} \cdot q_{v,sp} \cdot W_{s,sp}}{\rho_{t,i} \cdot q_{v,t} \cdot W_{s,t}} \right) \quad (5\text{-}3\text{-}9b)$$

$$P_{pr} = P_t \cdot \left(\frac{P_{s,sp}}{P_{s,t}} \right) \quad (5\text{-}3\text{-}9c)$$

The isentropic power referred to in eq. (5-3-9c) shall be calculated as:

$$P_{s,sp} = \rho_{sp,i} \cdot q_{v,sp} \cdot W_{s,sp} \quad (5\text{-}3\text{-}10)$$

and

$$P_{s,t} = \rho_{t,i} \cdot q_{v,t} \cdot W_{s,t} \quad (5\text{-}3\text{-}11)$$

Equation (5-3-12) calculates the predicted discharge pressure at site conditions for isentropic head from the test and parameters described above.

$$p_{d_{pr}} = p_{i,t} \cdot \left[1 + \left(\frac{\kappa_{mix} - 1}{\kappa_{mix}} \right) \cdot \left(\frac{W_{s_{pr}}}{\frac{\overline{R}}{MW_{mix}} \cdot T_i} \right) \right]^{\frac{\kappa_{mix}}{\kappa_{mix}-1}} \quad (5\text{-}3\text{-}12)$$

5-3.3.2 Dynamic Blower Power Prediction: Test Flow/Speed Not Matching Specified Flow/Speed. Mechanical or other limitations may require that test speed differ from specified speed.

Proper consideration of the impact of mechanical or associated losses on total power consumption shall limit the allowable difference to within ±4%. If there is a speed difference within this range, the corrective equations herein shall be used.

Considering the speed ratio permissible deviations described in eq. (3-5-1), and corollary eqs. (3-5-2) and (3-5-3), the following equations shall predict the inlet volumetric flow rate and isentropic head:

Inlet volumetric flow rate

$$q_{v,pr,1} = q_{v,t} \left(\frac{N_{pr}}{N_t} \right) \quad (5\text{-}3\text{-}13)$$

Isentropic head

$$W_{s,pr,1} = W_t \left(\frac{N_{pr}}{N_t} \right)^2 \quad (5\text{-}3\text{-}14)$$

NOTE: Use eqs. (3-5-4) and (3-5-5) to verify the selected test speed for the above equations. Subscript "1" is used herein to follow the use of the speed ratio calculation in the inlet volumetric flow and isentropic head calculations.

Extrapolation from test to predicted conditions shall therefore be calculated through the ratio of test to specified conditions of the inlet density, inlet volumetric flow rate, and isentropic head through the following equation for the predicted power as:

$$P_{pr} = P_t \cdot \left(\frac{\rho_{sp,i}}{\rho_{t,i}} \right) \cdot \left(\frac{q_{v,pr,1}}{q_{v_t}} \right) \cdot \left(\frac{W_{s_{pr},1}}{W_{s_t}} \right) \quad (5\text{-}3\text{-}15a)$$

Alternatively

$$P_{pr} = P_t \cdot \left(\frac{\rho_{sp,i} \cdot q_{v,pr,1} \cdot W_{s_{pr},1}}{\rho_{t,i} \cdot q_{v_t} \cdot W_{s_t}} \right) \quad (5\text{-}3\text{-}15b)$$

$$P_{pr} = P_t \cdot \left(\frac{P_{s,pr,1}}{P_{s,t}} \right) \quad (5\text{-}3\text{-}15c)$$

The isentropic power referred to in eq. (5-3-15c) shall be calculated as follows:

$$P_{s,pr,1} = \rho_{sp,i} \cdot q_{v,pr,1} \cdot W_{s_{pr},1} \quad (5\text{-}3\text{-}16)$$

The following equation calculates the predicted discharge pressure at site conditions from test and quantities above when a speed deviation applies:

Predicted discharge pressure

$$p_{d_{pr}} = p_{i,t} \cdot \left[1 + \left(\frac{\kappa_{mix} - 1}{\kappa_{mix}} \right) \cdot \left(\frac{W_{s_{pr},1}}{\frac{\overline{R}}{MW_{mix}} \cdot T_i} \right) \right]^{\frac{\kappa_{mix}}{\kappa_{mix}-1}} \quad (5\text{-}3\text{-}17)$$

5-3.4 Machine Mach Number

Paragraph 3-5.4 describes permissible deviations between test and specified operating conditions. The machine Mach number parameter prescribed there shall be calculated as

$$M_m = \frac{U_2}{\sqrt{\kappa_{mix} \cdot \frac{\overline{R}}{MW_{mix}} \cdot g_c \cdot T_i}} \quad (5\text{-}3\text{-}18)$$

Single stage (reference tip speed for a single impeller)

$$U_2 = \pi N D_2 \quad (5\text{-}3\text{-}19)$$

Multistage (the addition of the tip speed squared for each impeller)

$$(U_{sh})^2 = \sum (U_n{}^2) = \pi N \left[\sum (D_{2,n}{}^2) \right] \quad (5\text{-}3\text{-}20a)$$

$$U_2 = \sqrt{(U_{sh})^2} \quad (5\text{-}3\text{-}20b)$$

5.4 PD BLOWERS

The method for testing and predicting the performance of a PD blower is detailed herein. At its core, the specified flow and total pressure ratio shall be matched during the test. Nonmandatory Appendix C illustrates the calculations and the procedure to determine thermodynamic conditions and illustrates the order of the calculation methods.

5-4.1 Adjustment of Results to Specified Conditions

It is unlikely that the actual test conditions will duplicate specified conditions. Predictions of power at specified conditions shall be made by extrapolation of measured parameters to the specified conditions. Power predictions shall be adjusted to specified conditions for deviations in flow, inlet pressure, and pressure ratio. The method used for adjustments assumes that the blower efficiency remains unchanged for the deviations within the limits of Table 3-5.4-2.

5-4.2 Test Pressure Ratio

The pressure ratio during the test shall be set equal to the specified pressure ratio and maintained within the limits given in Table 3-5.4-2 by adjusting the discharge pressure. Failure to maintain the required pressure ratio shall constitute an invalid test. The pressure ratio at specified and test conditions shall be calculated using total conditions.

$$r_p = \frac{p_{d,\text{tot}}}{p_{i,\text{tot}}} \tag{5-4-1}$$

5-4.3 Test Flow Rate

The volumetric flow rate into the blower package at the reference boundary during the test shall be set equal to the specified flow rate and maintained within the limits given in Table 3-5.4-2 by adjusting the blower speed. The volumetric flow rate should be either directly specified or calculated from the specified mass flow rate and inlet density. The required flow rate should be attained by modulation of a VFD or similar device if variable speed is specified, or by changing sheaves if belt-driven constant speed is specified.

For constant-speed blower packages, either belt driven or direct coupled, the inlet volumetric flow rate at specified conditions shall equal the inlet volumetric flow rate at test conditions for calculation of projected performance

$$q_{v_{sp}} \equiv q_{v_t} \tag{5-4-2}$$

5-4.4 Power Predictions

It is recognized that some elements of the total wire power input to a packaged blower are independent of shaft speed and ambient pressure, e.g., the power input to a separately driven cooling fan and power consumed by regulation systems.

Note that deviations in discharge temperature will not affect speed or pressure ratio for the test.

5-4.4.1 Isentropic Power Predictions. For variable-speed blowers, the power projection shall be based on specified and test volumetric flow rate for predicting power at specified conditions. The predicted power shall be corrected for differences in flow rate, inlet conditions, and density.

Predicted power for variable speed blowers

$$P_{pr} = P_t \cdot \left(\frac{\rho_{sp,i}}{\rho_{t,i}}\right) \cdot \left(\frac{q_{v_{sp}}}{q_{v_t}}\right) \cdot \left(\frac{W_{s_{sp}}}{W_{s_t}}\right) \tag{5-4-3a}$$

Alternatively

$$P_{pr} = P_t \cdot \left(\frac{\rho_{sp,i} \cdot q_{v_{sp}} \cdot W_{s_{sp}}}{\rho_{t,i} \cdot q_{v_t} \cdot W_{s_t}}\right) \tag{5-4-3b}$$

Alternatively

$$P_{pr} = P_t \cdot \left(\frac{P_{s,sp}}{P_{s,t}}\right) \tag{5-4-3c}$$

For constant-speed blowers, the power projection shall be based on actual test volumetric flow rate for predicting power at specified conditions. The predicted power shall be corrected for differences in inlet conditions and density.

Predicted power for constant-speed blowers

$$P_{pr} = P_t \cdot \left(\frac{\rho_{sp,i}}{\rho_{t,i}}\right) \cdot \left(\frac{W_{s_{sp}}}{W_{s_t}}\right) \tag{5-4-4}$$

5-4.4.2 Predicting Discharge Pressure and Flow Rates. By definition, the predicted inlet volumetric flow rate shall be equal to the test inlet volumetric flow rate within the bounds of the test point defined in Table 3-5.4-2.

$$q_{v,i,pr} = q_{v,i,t}$$

The predicted static discharge pressure at specified inlet conditions shall be calculated using the specified inlet pressure and the test pressure ratio

$$p_{d,pr,\text{static}} = r_{p,t} \cdot p_{i,sp,\text{static}} \tag{5-4-5}$$

$$p_{d,pr,\text{static},ga} = p_{d,pr,\text{static}} - p_{a,sp} \tag{5-4-6}$$

The predicted mass flow rate at specified inlet conditions shall be calculated using the test inlet volumetric flow rate and the inlet density at specified conditions:

$$q_{m,pr} = q_{v,t} \cdot \rho_{sp,i} \tag{5-4-7}$$

The standard flow rate at specified standard conditions shall be calculated from the test inlet flow rate and the appropriate thermodynamic conditions:

$$q_{pr,\text{std}} = q_{v,t} \cdot \frac{p_{a,sp} - p_{vp,sp}}{p_{\text{std}} - p_{sv,\text{std}} \cdot \text{RH}_{\text{std}}} \cdot \frac{T_{std}}{T_{i,sp}} \cdot \frac{p_{i,sp}}{p_{a,sp}} \quad (5\text{-}4\text{-}8)$$

5-4.5 Deviation From Specified Data

Should the deviation between specified data and test data exceed the values of Table 3-5.4-2, the method for adjusting the measured data to the specified conditions shall be agreed to by the parties and should be based on the machine characteristics determined by the blower manufacturer if agreed to by the parties.

5-4.5.1 Volumetric Flow Rate Correction for Speed. Corrections to volumetric flow rate shall be required when the difference between the test inlet conditions and the specified inlet conditions result in the inability to operate a PD blower system at the speed required to meet the required inlet volumetric flow rate without causing mechanical damage or motor overload. This methodology shall not be used to compensate for the difference between specified capacity and actual capacity for systems specified to operate at constant speed at site conditions.

$$q_{pr} = q_t \cdot \left(\frac{N_{sh,sp} - b}{N_{sh,t} - b} \right) \quad (5\text{-}4\text{-}9)$$

NOTE: The shaft designation "sh" in the terms $N_{sh,sp}$ and $N_{sh,t}$ shall be either the operating blower shaft speed or the motor shaft speed, with appropriate belt slip consideration as required.

The volumetric flow rate at any speed can be calculated from

$$q_v = m \cdot (N - b) \quad (5\text{-}4\text{-}10)$$

where

b = the x-intercept of the linear correlation between rotational speed and volumetric flow rate.

m = the slope of the linear correlation between rotational speed and volumetric flow rate

The values for m and b are obtained as follows:

(a) Modulate blower speed to operate the blower at two different volumetric flow rates at the specified pressure ratio. Two test flow rates are required for the linear interpolation. One test flow rate shall be approximately 90% of the specified flow rate, and one flow rate shall be approximately 80% of the specified flow rate. No deviation more than 20% below the target flow shall be permitted to provide assurance of linearity.

$$m = \frac{q_{v.2} - q_{v.1}}{N_2 - N_1} \quad (5\text{-}4\text{-}11)$$

$$b = N_1 - \frac{q_{v.1}}{m} \quad (5\text{-}4\text{-}12)$$

(b) By agreement of the parties, data and correlations from previously conducted tests may be used to determine m and b, provided appropriate corrections are made to compensate for differences between the specified pressure ratio and the pressure ratio in the previous tests.

(c) Only if test data is not available and by agreement of the parties, the value of m may be assumed to be 1.0 and the value of b may be assumed to be zero. This shall be noted in the test report as "estimated flow."

NOTE: This correction methodology is not applicable to direct coupled constant speed blower systems.

Section 6
Report of Results

6-1 GENERAL REQUIREMENTS

The report shall be a document prepared in suitable form to formally present clearly and concisely the test data observed and computed. The report shall present sufficient information to demonstrate that all objectives of the tests have been obtained and the required methodology implemented. The report shall follow the general outline given in the following paragraphs.

Copies of the original test data log, certificates of instrument calibration, prime mover data as needed, description of test arrangement and instrumentation, and any special written agreements pertaining to the test or the computation of results shall be included.

The report should include the following distinct sections:

(a) executive summary
(b) detailed report of the test
(c) appendices and illustrations

6-2 EXECUTIVE SUMMARY

The executive summary should contain, at minimum

(a) date(s) of test

(b) brief description of the object of the test, test results, specified operating conditions and performance requirements, specified test points, and conclusions reached

(c) detailed description of the blower system, including type of blower, motor, control or flow modulation method, and description of all accessories and auxiliary equipment

(d) test coordinator(s) signature(s) and date

(e) reviewer(s) and report writer(s) signature and date

(f) witness(es), purchaser(s) or other party(ies) signature verifying concurrence with reported raw data

(g) final report, after review of results, may include approval, signature, and date

6-3 DETAILED REPORT

The detailed report of the test should provide all required data and information necessary to verify that the test and analysis of the test are in conformance with this Code and the requirements of all contracts, specifications, and other agreements between the parties. Any deviations from the requirements of this Code must be explicitly noted, along with the reason for the deviation, the effect of the deviation, and the resolution between the parties as to the acceptance of the deviations.

Pipe sizes, including inside diameters, inlet louver dimensions, blower impeller dimensions, cooling apparatus or methods, type and locations of any flow conditioners or straighteners, and the locations of inlet and discharge airstreams should be identified. All electric, process, and fluid components inside the test reference boundary as defined in subsection 3-5 should be identified. System components required for operation but not included in the test apparatus or differing from the final installed configuration shall be identified per the tables in subsection 3-5. Any system components outside the reference boundary that could impact the test results or blower performance should be identified.

6-3.1 Detailed Report: Instruments or Test Apparatus

For all measurements, the report must include the following information for each instrument or test apparatus:

(a) type of instrument, operating principle, output signal, and local indication (if any)

(b) manufacturer name, model number, and serial number

(c) critical dimensions of the instrument

(d) fluctuations of the measurements

(e) uncertainty of the instrument and measurement

(f) range of the instrument

(g) smallest division on the instrument's scale

(h) last calibration date, calibrating agency, and copies of certificates of calibration

6-3.2 Detailed Report: Measurements

The detailed report should include

(a) average test point data for each measurement, including time of the measurement and deviations from specified values as identified in subsection 3-5

(b) measured data for each test point for all blower types, including, as a minimum

(1) barometric pressure, ambient static temperature, and relative humidity or wet bulb temperature

(2) inlet static pressure and inlet static temperature if the system inlet reference boundary is not at ambient conditions (or total if measured directly)

(3) discharge static pressure and discharge static temperature (or total if measured directly)

(4) flowmeter differential pressure for differential pressure class meters or mass flow measurement for other types

(5) voltage, current, power factor, and power measurements for each phase of all electric power inputs crossing the system reference boundary

(6) flow rates and inlet and discharge temperature of any cooling flow streams crossing the system reference boundary

(7) operating speed of the blower and motor if required by para. 3-3.7

(c) all significant calculated and derived values, including the uncertainty of each

(1) for all blowers, the reported data for each test point shall include, as a minimum,

(-a) total temperature and pressure for each measurement point

(-b) mole fraction of water vapor, gas constant, and molecular weight

(-c) inlet, discharge, and average specific heat

(-d) mixture ratio of specific heats, κ

(-e) ambient, inlet, and discharge air density at test and specified conditions

(-f) discharge mass flow rate as measured and corrected to specified units if different from test units of measure

(-g) inlet volumetric flow rate at the reference boundary as measured and corrected to specified units if different from test units of measure

(-h) pressure ratio across the reference boundary

(-i) total measured electric active power

(-j) isentropic power at specified and test conditions

(-k) predicted volumetric flow rate at specified conditions

(-l) predicted pressure ratio and discharge pressure at specified conditions

(-m) predicted power at specified conditions

(-n) power at specified conditions adjusted to include differences between test and specified system configurations, including extrapolations to compensate for speed or other mechanical limitations

(-o) predicted mass flow rate at specified conditions

(-p) additional test parameters or results required by specification but not included in this Code's requirements

(2) for dynamic blowers only, the reported data for each test point shall also include

(-a) isentropic head

(-b) inlet volumetric flow rate

(-c) machine Mach number

(-d) rise to surge at constant speed and vane or valve configuration

(d) tabular and graphic presentation of the test results

(e) discussion and details of the test results' uncertainties

(f) discussion of the test results, deviation from specified performance, and conclusions

6-4 APPENDICES

Appendices and illustrations are optional and may be provided as required to clarify description of the circumstances, equipment, and methodology of the test; description of methods of calibrations of instruments; outline of details of calculations including a sample set of computations, descriptions, and statements depicting special testing apparatus; result of preliminary inspections and trials; and any supporting information required to make the report a complete, self-contained document of the entire undertaking. Reference information of interest to the parties but not required by the Code for predicting performance may be included in the appendices.

Section 7
Test Uncertainty

7-1 OVERVIEW

Uncertainty analysis is a procedure used to quantify the accuracy of test results. Pretest and post-test uncertainty analyses are indispensable methods to determine the quality of the performance test. The parties of the performance test shall agree to the quality of the test and to the requirements for a pretest and/or post-test uncertainty analysis.

Evaluating test uncertainty provides a measure of the quality of the test results and calculations. It helps identify actions needed to achieve the desired uncertainty. Because the contribution of each measurement to overall uncertainty is identified, improvements can be made to these parameters to achieve the desired level of test accuracy. Uncertainty analysis also provides test-run validation, demonstrates compliance with agreements, and determines sensitivity, θ_i, of each parameter.

The uniqueness of this Code's test objectives precludes exhaustive treatment of uncertainty in this Code. The user should refer to ASME PTC 19.1, the primary reference for uncertainty calculations, for additional detailed information and reference. Any uncertainty analysis method that conforms to ASME PTC 19.1 shall be acceptable.

ASME PTC 19.1 includes discussions and methods that enable the user to select an appropriate uncertainty model for analysis and reporting test results. It defines, describes, and illustrates the terms and methods used to provide meaningful estimates of the uncertainty of measurements and performance test results.

The uncertainty analysis should be tailored to meet individual test objectives. The following discussion describes the calculation method in general terms. The sample calculations presented in Nonmandatory Appendix A are intended to demonstrate the methodology for reference information.

The following is a brief summary of the step-by-step calculation procedure that shall be conducted before and after each test, as agreed between parties, as presented in ASME PTC 19.1.

(a) Step 1. Define the measurement process.

(1) Review test objectives and test duration.

(2) List all independent measurement parameters and the associated nominal levels.

(3) List all calibrations and instrument setups.

(4) Define the functional relationship between the independent parameters and the test result.

(b) Step 2. List elemental error sources.

(1) Prepare a list of all possible measurement error sources.

(2) Group error sources according to calibration, data acquisition, or data reduction.

(c) Step 3. Estimate elemental errors.

(1) Obtain estimate of each error in Step 2.

(2) Classify as systematic or random error.

(d) Step 4. Calculate systematic uncertainty, $b_{\overline{x}_i}$, and random uncertainty, $s_{\overline{x}_i}$, for each parameter.

(e) Step 5. Calculate systematic uncertainty contribution, $\left(b_{\overline{x}_i}\theta_i\right)^2$, and random uncertainty contribution, $\left(s_{\overline{x}_i}\theta_i\right)^2$, for each parameter.

(f) Step 6. Calculate combined uncertainty of the result, u_R.

(g) Step 7. Calculate the expanded uncertainty, $U_{R,95}$.

(h) Step 8. Report.

(1) symbol(s) used in the calculations

(2) description of parameter

(3) units

(4) nominal value (average of measurements)

(5) systematic standard uncertainty, $b_{\overline{x}_i}$

(6) standard deviation of the mean (random standard uncertainty), $s_{\overline{x}_i}$

(7) sensitivity, θ_i

(8) systematic standard uncertainty contribution of the combined uncertainty of the result, $\left(b_{\overline{x}_i}\theta_i\right)^2$

(9) random standard uncertainty contribution of the combined uncertainty of the result, $\left(s_{\overline{x}_i}\theta_i\right)^2$

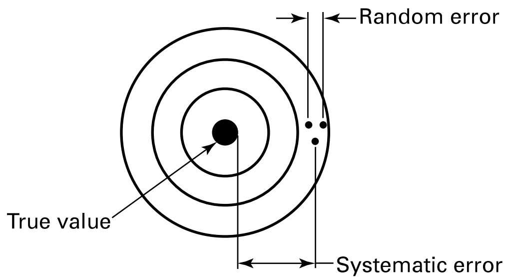
(10) summary report table displaying information associated with the result, as shown in the examples in Nonmandatory Appendix A, including

(-a) combined uncertainty of the result, u_R

(-b) total absolute uncertainty, $U_{R,95}$

Finalize the uncertainty analysis pertaining to the performance test and the conclusion between the parties regarding acceptance of the quality of the test.

Figure 7-2.1.1-1 Measurement Error Diagram



7-2 UNDERSTANDING TEST UNCERTAINTY

7-2.1 Uncertainty Versus Error

Random and systematic "uncertainties" are calculations of the elemental "error" sources. The objective of this Section is to calculate test uncertainty and to concentrate on providing an understanding of uncertainty.

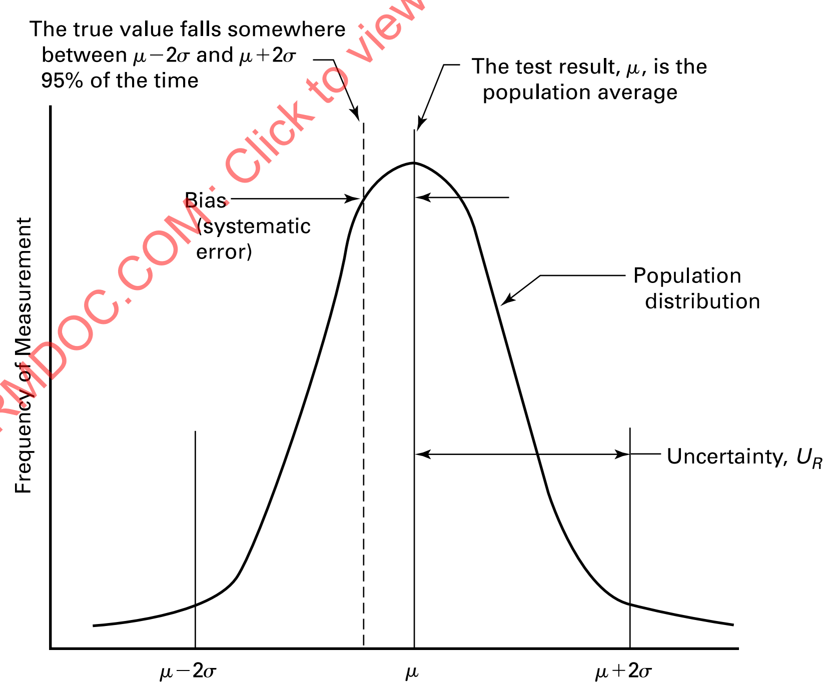
7-2.1.1 Random and Systematic Components of Measurement Errors. The total error for each measurement has two components, random and systematic, as shown in Figure 7-2.1.1-1. Values of the two components shall be determined by calculation or estimation of each of the contributing error sources.

Repeated measurements of the same quantity by the same measuring system operated by the same personnel do not yield identical values. This is the manifestation of random error. Random error is described by a normal (Gaussian) probability distribution, as illustrated by Figure 7-2.1.1-2.

Systematic error is a characteristic of the measurement system. Systematic uncertainty is not random; it is an essentially fixed (although unknown) quantity in any experiment or test that uses a specific instrument system and data reduction and calculation procedures.

When the magnitude and sign of a systematic error is known, it shall be handled as a correction to the measured value, with the corrected value used to calculate the test result. Systematic uncertainty estimates considered in uncertainty analysis attempt to cover those systematic errors whose magnitudes are unknown. Examples of systematic errors intended to be included in the

Figure 7-2.1.1-2 Gaussian Probability Distribution Curve



Legend:
μ = true average of a population
σ = true standard deviation of a population

GENERAL NOTE: The true value (dashed line) is somewhere within the 2σ region with 95% confidence.

uncertainty analysis are drift in calibration of a pressure transmitter, the errors resulting from calculation procedure approximations, and the potential errors made in estimating values for unmeasured parameters.

There is a high probability (usually 95%) that a band defined by the measured value ± the uncertainty shall include the true value.

7-2.2 Systematic Standard Uncertainty, b_i

The systematic standard uncertainty, b_i, is an estimate, based on experience, of the error of the average value not eliminated through calibration. The systematic error can be reduced with better instrument calibration and/or increasing the quantity of instruments. The instrument accuracy or "bias," B_x, is an example of a systematic error. This accuracy is typically provided by the instrument manufacturer and is often expressed as a percent of reading and/or percent of full scale.

7-2.2.1 Estimating Systematic Uncertainties, b_i. Systematic uncertainties shall be estimated using the experience of the parties and the suggestions and analyses presented in ASME PTC 19.1; these should reflect the 95% confidence level used for Performance Test Codes. For assistance in establishing reasonable values for the systematic uncertainty, consider the following:

(a) for normally distributed values, based on large degrees of freedom and symmetric b_i, a 95% confidence level can be estimated by $b_i = \left(\frac{B_x}{2}\right)$

(b) the cumulative test experience of the parties

(c) the calibration lab's accuracy and experience with various instrument types

(d) experience with duplicate instruments measuring the same quantity, or different types of instruments measuring the same quantity

(e) the DAQ used, including the instrumentation and complete measuring circuit with the digital/analog conversation and measurement

(f) the calibration of the "eye" for manual readings, including repeatability

7-2.3 Combining Systematic Uncertainties

When all the systematic influences have been evaluated at the 95% confidence level, they shall be combined into a single factor, ($b_{\overline{x}}$), for the measurement by the root sum square method, as defined in eq. (7-2-1).

$$b_{\overline{x}} = \sqrt{\sum_{i=1}^{i} (b_i)^2} \tag{7-2-1}$$

7-2.4 Correlated vs. Uncorrelated Systematic Uncertainty

Equation (7-2-1) assumes that the systematic standard uncertainties of the measured parameters are all independent of each other. There are, however, many practical situations where this is not true; for example, when using the same instruments to measure different parameters, or when using multiple instruments of the same type that have been calibrated against the same standard to measure the same parameter. In these cases, some of the systematic errors are said to be correlated, and the combined systematic uncertainty of the average measured value should not be reduced using the root sum square method; rather, it should be considered to be the uncertainty of a single instrument measuring the parameter in question. The parties should refer to ASME PTC 19.1 for details on calculating correlation effects, and to the examples shown later in this Section.

7-2.5 Random Standard Uncertainty of a Sample, $s_{\overline{x}}$

Several error sources associated with the test instrumentation are reflected as scatter in the data over the test-time interval. It is generally assumed that the scatter is normally distributed and can be approximated statistically. For a sample measurement, the mean value is given by

$$\overline{X} = \frac{\sum_{i=1}^{N} X_i}{N} \tag{7-2-2}$$

where X_i represents the value of each individual measurement in the sample and N is the number of sample measurements.

The standard deviation of the sample, s_{x_i}, is given by

$$s_{X_i} = \sqrt{\sum_{i=1}^{N} \frac{(X_i - \overline{X})^2}{N - 1}} \tag{7-2-3}$$

The random standard uncertainty, $s_{\overline{x}_i}$, is the standard deviation of the mean, or

$$s_{\overline{X}_i} = \frac{s_X}{\sqrt{N}} \tag{7-2-4}$$

The value of $N - 1$ in eq. (7-2-3) is referred to as the degrees of freedom. Increasing the number of measurements, and thus the degrees of freedom, improves the accuracy of the statistical calculations and reduces the random standard uncertainty of the sample. For a 95% confidence level, at least 30 measurements should be made.

In practice, much of the data taken during a test may be from single measurements or an average of measurements over a short period of time. In such situations, the degrees of freedom are quite small and the corresponding confidence level of the random standard uncertainty is lower than the desired 95% confidence level. In that case, additional measurements should be taken at steady-state conditions, prior to the test run and/or immediately thereafter, to provide enough data to produce a higher confidence level. Additional guidance is available in ASME PTC 19.1.

7-2.6 Sensitivity Coefficients, Θ_i

The sensitivity coefficients, Θ_i, are a measure of the sensitivity of the calculated result to the changes in the parameter in question. In practice, because a performance test typically requires the use of a complex set of iterative calculation algorithms, the sensitivity of a parameter is determined numerically by perturbing the measured value of that parameter by a small amount and recording the change in the calculated result. The sensitivity shall be calculated as the change in the calculated result divided by the change in the measured parameter. Sensitivities can be calculated as either relative or absolute, but care must be taken to maintain consistency in units throughout the overall uncertainty calculation. Sensitivities of components (variables) within calculation equations are determined by performing the partial derivative with respect to the individual component or variable.

7-2.7 Absolute Systematic, b_R, and Random Standard, s_R, Uncertainty

The absolute systematic and random standard uncertainty shall be calculated by the absolute standard uncertainty contributions as follows:

Absolute systematic uncertainty:

$$b_R = \sqrt{\sum_{i=1}^{i} \left(b_{\bar{x}_i} \cdot \Theta_i\right)^2} \tag{7-2-5}$$

Absolute random standard uncertainty:

$$s_R = \sqrt{\sum_{i=1}^{i} \left(s_{\bar{x}_i} \cdot \Theta_i\right)^2} \tag{7-2-6}$$

7-2.8 Combining Absolute Systematic, b_R, and Random Standard, s_R, for Combined Uncertainty, u_R

The combined uncertainty, u_R, for each parameter measured shall be calculated from the root sum square of the systematic and random components. At this point the random standard uncertainty calculations have been made on the one standard deviation basis expressed by eq. (7-2-7).

$$u_R = \sqrt{(b_R)^2 + (s_R)^2} \tag{7-2-7}$$

7-2.9 Calculating Expanded Uncertainty of the Result, U_R

Assuming the values are normally distributed, based on large degrees of freedom and symmetric systematic uncertainty, the expanded uncertainty of the result at a 95% confidence level is given by eq. (7-2-8).

$$u_{R,95} = 2u_R \tag{7-2-8}$$

For cases where the above assumptions are not valid, refer to ASME PTC 19.1.

Mandatory Appendix I
Airflow Conversions

I-1 OBJECT AND SCOPE

This Appendix provides an example of rigorous determination of volumetric flow rate at specified conditions based on a standard volume flow.

I-1.1 Given Conditions

(a) Standard Conditions. The following are the standard conditions used in this example:

Conditions	Values
Temperature, T_{std}	68.0°F
Pressure, p_{std}	$14.700 \frac{\text{lbf}}{\text{in.}^2}\text{abs}$
Relative humidity, RH_{std}	36%

(b) Specified Conditions. The following are the specified conditions used in this example:

Conditions	Values
Volumetric flow rate, $q_{sp,std}$	10,000 SCFM (ft^3/min at standard condition)
Inlet temperature, $T_{i,sp}$	40.0°F
Barometric pressure, $p_{a,sp}$	$13.950 \frac{\text{lbf}}{\text{in.}^2}\text{abs}$
Inlet pressure, $p_{i,sp}$	$13.500 \frac{\text{lbf}}{\text{in.}^2}\text{abs}$
Relative humidity, RH_{std}	25%

I-1.2 Objective of Calculations

The objective of the calculations in this Appendix is to determine the volumetric flow rate at specified conditions that will deliver the same mass flow of dry air as that implied by the standard volumetric flow rate specified in I-1.1(b). The saturated vapor pressure can be determined by referring to the saturation line of the ASME Steam Tables; alternatively, the empirical eq. (5-2-2) (repeated herein) can be used to determine the saturated vapor pressure with accuracy comparable to the steam tables for the temperature range of 32.02°F to 130°F.

I-2 CALCULATIONS

I-2.1 Saturated Vapor-Pressure Beta Coefficients

The empirical function is based on temperature, T, in Rankine units.

$$\beta_{sv} = \frac{-7{,}202.2367}{T(°\text{R}) - 70.431} \tag{5-2-2 [repeated]}$$

NOTE:

$T\,(°R)$ refers to a function argument for temperature expressed exclusively in degrees Rankine for this empirical function that leads to determination of saturated vapor pressure in air. Other functions may use tabs as a function argument for temperature expressed in absolute scale using units that correspond to the units system being used for the calculations.

(a) Standard Condition

$$\beta_{sv,\mathrm{std}} = \beta_{sv}\left(T_{\mathrm{std}}[^\circ\mathrm{R}]\right) = \frac{-7{,}202.2367}{(68+459.67)\,^\circ\mathrm{R} - 70.431} = -15.7516$$

(b) Specified Condition

$$\beta_{sv,sp} = \beta_{sv}\left(T_{i,sp}[^\circ\mathrm{R}]\right) = \frac{-7{,}202.2367}{(40+459.67)\,^\circ\mathrm{R} - 70.431} = -16.7791$$

I-2.2 Saturated Vapor Pressures

The empirical function is based on the beta coefficient.

$$p_{sv}(T[^\circ\mathrm{R}]) = 2.34908 \cdot 10^6 \cdot e^{\beta_{sv}(T[^\circ\mathrm{R}])}\frac{\mathrm{lbf}}{\mathrm{in.}^2}\mathrm{abs}$$

(a) Standard Condition

$$p_{sv,\mathrm{std}} = p_{sv}(T_{\mathrm{std}}[^\circ\mathrm{R}]) = 2.34908 \cdot 10^6 \cdot e^{-15.7516} = 0.3390\frac{\mathrm{lbf}}{\mathrm{in.}^2}\mathrm{abs}$$

(b) Specified Condition

$$p_{sv,sp} = p_{sv}\left(T_{i,sp}[^\circ\mathrm{R}]\right) = 2.34908 \cdot 10^6 \cdot e^{-16.7791} = 0.1213\frac{\mathrm{lbf}}{\mathrm{in.}^2}\mathrm{abs}$$

I-2.3 Air Mixture Vapor Pressures

This function is based on saturated vapor pressure and relative humidity.

$$p_{vp}(T[^\circ\mathrm{R}], \mathrm{RH}) = p_{sv}(T[^\circ\mathrm{R}]) \cdot \mathrm{RH}$$

(a) Standard Condition

$$\begin{aligned} p_{vp,\mathrm{std}} &= p_{vp}(T_{\mathrm{std}}[^\circ\mathrm{R}], \mathrm{RH}_{\mathrm{std}}) \\ &= p_{sv}(T_{\mathrm{std}}[^\circ\mathrm{R}]) \cdot \mathrm{RH}_{\mathrm{std}} \\ &= 0.3390\frac{\mathrm{lbf}}{\mathrm{in.}^2}\mathrm{abs} \cdot 0.36 \\ &= 0.1220\frac{\mathrm{lbf}}{\mathrm{in.}^2}\mathrm{abs} \end{aligned}$$

(b) Specified Condition

$$\begin{aligned} p_{vp,sp} &= p_{vp}(T_{i,sp}[^\circ\mathrm{R}], \mathrm{RH}_{sp}) \\ &= p_{sv}(T_{i,sp}[^\circ\mathrm{R}]) \cdot \mathrm{RH}_{sp} \\ &= 0.1213\frac{\mathrm{lbf}}{\mathrm{in.}^2}\mathrm{abs} \cdot 0.25 \\ &= 0.0303\frac{\mathrm{lbf}}{\mathrm{in.}^2}\mathrm{abs} \end{aligned}$$

I-2.4 Air Mixture Molecular Weights

The molecular weight of the air mixture is based on mole-fraction proportions of dry air and water vapor in the mixture.

MW_{da} = 28.970 lbm/lbmol
MW_{vp} = 18.015 lbm/lbmol
x_{vp} = mole fraction of water vapor in mix = vapor pressure/total pressure

$$x_{vp}(T[°R], \text{RH}, p) = \frac{p_{sv}(T[°R] \cdot \text{RH})}{p} = \frac{p_{vp}(T[°R], \text{RH})}{p}$$

$$\text{MW}_{\text{mix}}(T[°R], \text{RH}, p) = \text{MW}_{vp} \cdot x_{vp}(T[°R], \text{RH}, p) + \text{MW}_{da} \cdot \left[1 - x_{vp}(T[°R], \text{RH}, p)\right]$$

(a) Standard Condition

$$x_{vp,\text{std}} = x_{vp}\left(T_{\text{std}}, \text{RH}_{\text{std}}, p_{\text{std}}\right) = \frac{p_{vp,\text{std}}}{p_{\text{std}}} = \frac{0.1220 \frac{\text{lbf}}{\text{in.}^2}\text{abs}}{14.700 \frac{\text{lbf}}{\text{in.}^2}\text{abs}} = 0.0083$$

$$\begin{aligned}\text{MW}_{\text{mix,std}} &= \text{MW}_{\text{mix}}\left(T_{\text{std}}, \text{RH}_{\text{std}}, p_{\text{std}}\right) = \text{MW}_{\text{water}} \cdot x_{vp,\text{std}} + \text{MW}_{da}(1 - x_{vp,\text{std}}) \\ &= 18.015 \frac{\text{lbm}}{\text{lbmol}} \cdot 0.0083 + 28.970 \frac{\text{lbm}}{\text{lbmol}} \cdot (1 - 0.0083) = 28.879 \frac{\text{lbm}}{\text{lbmol}}\end{aligned}$$

(b) Specified Condition

$$x_{vp,sp} = x_{vp}\left(T_{i,sp}, \text{RH}_{sp}, p_{i,sp}\right) = \frac{p_{vp,sp}}{p_{i,sp}} = \frac{0.0303 \frac{\text{lbf}}{\text{in.}^2}\text{abs}}{13.500 \frac{\text{lbf}}{\text{in.}^2}\text{abs}} = 0.0022$$

$$\begin{aligned}\text{MW}_{\text{mix},sp} &= \text{MW}_{\text{mix}}\left(T_{i,sp}, \text{RH}_{sp}, p_{i,sp}\right) = \text{MW}_{vp} \cdot x_{vp,sp} + \text{MW}_{da}\left(1 - x_{vp,sp}\right) \\ &= 18.015 \frac{\text{lbm}}{\text{lbmol}} \cdot 0.0022 + 28.970 \frac{\text{lbm}}{\text{lbmol}} \cdot (1 - 0.0022) = 28.945 \frac{\text{lbm}}{\text{lbmol}}\end{aligned}$$

I-2.5 Air Mixture Densities

These densities are derived from the ideal gas law.

Universal Gas Constant, $\overline{R} = 1{,}545.3488 \frac{\text{ft} \cdot \text{lbf}}{\text{lbmol} \cdot °\text{R}}$

$$\rho(T[°R], T, \text{RH}, p) = \frac{p}{\frac{\overline{R}}{\text{MW}_{\text{mix}}(T[°\text{R}], \text{RH}, p)} \cdot T}$$

NOTE: With MW_{mix} already determined, p and T can be used with any units that are consistent with the units for the chosen universal gas constant.

(a) Standard Condition

$$\rho_{\text{std}} = \rho\left(T_{\text{std}}, \text{RH}_{\text{std}}, p_{\text{std}}\right) = \frac{p_{\text{std}}}{\frac{R_g}{\text{MW}_{\text{mix,std}}} \cdot T_{\text{std}}} = \frac{14.700 \frac{\text{lbf}}{\text{in.}^2} \cdot \frac{144 \text{ in.}^2}{\text{ft}^2}}{\frac{1{,}545.3488 \frac{\text{ft} \cdot \text{lbf}}{\text{lbmol} \cdot °\text{R}}}{28.8790 \frac{\text{lbm}}{\text{lbmol}}} \cdot (68 + 459.67)\ °\text{R}} = 0.07497 \frac{\text{lbm}}{\text{ft}^3}$$

(b) Specified Condition

$$\rho_{i,sp} = \rho\left(T_{i,sp}, \text{RH}_{sp}, p_{i,sp}\right) = \frac{p_{i,sp}}{\frac{R_g}{\text{MW}_{\text{mix},sp}} \cdot T_{i,sp}} = \frac{13.500 \frac{\text{lbf}}{\text{in.}^2} \cdot \frac{144 \text{ in.}^2}{\text{ft}^2}}{\frac{1{,}545.3488 \frac{\text{ft} \cdot \text{lbf}}{\text{lbmol} \cdot °\text{R}}}{28.9453 \frac{\text{lbm}}{\text{lbmol}}} \cdot (40 + 459.67)\ °\text{R}} = 0.07287 \frac{\text{lbm}}{\text{ft}^3}$$

I-2.6 Air Mixture Humidity Ratios, HR, Specific Humidities, SH

This is the ratio of the mass of air to the mass of water in the mixture. This ratio shall allow separation of the mass flow of water and the mass flow of dry air from the mass flow of an air mixture.

$$\mathrm{SH}_{\mathrm{mix}} = \mathrm{HR}_{\mathrm{mix}} = \left(\frac{\mathrm{mass}_{vp}}{\mathrm{mass}_{da}}\right)_{\mathrm{mix}}$$

$$\mathrm{HR}_{\mathrm{mix}}(T[°\mathrm{R}],\ \mathrm{RH},\ p) = \left(\frac{\mathrm{MW}_{vp}}{\mathrm{MW}_{da}}\right)\cdot\frac{p_{\mathrm{sat}}(T[°\mathrm{R}], \mathrm{RH}, p)\cdot \mathrm{RH}}{p - p_{\mathrm{sat}}(T[°\mathrm{R}], \mathrm{RH}, p)\cdot \mathrm{RH}}$$

$$\mathrm{HR}_{\mathrm{mix}} = \left(\frac{\mathrm{MW}_{vp}}{\mathrm{MW}_{da}}\right)\cdot\frac{p_{vp}(T[°\mathrm{R}], \mathrm{RH}, p)}{p - p_{vp}(T[°\mathrm{R}], \mathrm{RH}, p)}$$

(a) Standard Condition

$$\mathrm{HR}_{\mathrm{mix,std}} = \mathrm{HR}_{\mathrm{mix}}\left(T_{\mathrm{std}},\ \mathrm{RH}_{\mathrm{std}},\ p_{\mathrm{std}}\right) = \left(\frac{\mathrm{MW}_{vp}}{\mathrm{MW}_{da}}\right)\cdot\frac{p_{vp,\mathrm{std}}}{p_{\mathrm{std}} - p_{vp,\mathrm{std}}}$$

$$= \left(\frac{18.015\frac{\mathrm{lbm}}{\mathrm{lbmol}}}{28.970\frac{\mathrm{lbm}}{\mathrm{lbmol}}}\right)\cdot\frac{0.1220\frac{\mathrm{lbf}}{\mathrm{in.}^2}\mathrm{abs}}{(14.700 - 0.1220)\frac{\mathrm{lbf}}{\mathrm{in.}^2}\mathrm{abs}} = 0.00521$$

(b) Specified Condition

$$\mathrm{HR}_{\mathrm{mix},sp} = \mathrm{HR}_{\mathrm{mix}}\left(T_{i,sp},\ \mathrm{RH}_{sp},\ p_{i,sp}\right) = \left(\frac{\mathrm{MW}_{\mathrm{water}}}{\mathrm{MW}_{\mathrm{air}}}\right)\cdot\frac{p_{vp,sp}}{p_{i,sp} - p_{vp,sp}}$$

$$= \left(\frac{18.015\frac{\mathrm{lbm}}{\mathrm{lbmol}}}{28.970\frac{\mathrm{lbm}}{\mathrm{lbmol}}}\right)\cdot\frac{0.0304\frac{\mathrm{lbf}}{\mathrm{in.}^2}\mathrm{abs}}{(13.500 - 0.0304)\frac{\mathrm{lbf}}{\mathrm{in.}^2}\mathrm{abs}} = 0.0014$$

I-2.7 Mass Flow of Mixture at Standard Conditions

This is the mass flow of the mixture from the specified standard volumetric flow rate.

$$q_{m,\mathrm{mix}}(q,\ T[°\mathrm{R}],\ T,\ \mathrm{RH},\ p) = q\cdot\rho(T[°\mathrm{R}],\ T,\ \mathrm{RH},\ p)$$

For the standard condition (in which volumetric flow rate is specified)

$$q_{m,\mathrm{mix,std}} = q_{m,\mathrm{mix}}\left(q_{sp,\mathrm{std}},\ T_{\mathrm{std}},\ \mathrm{RH}_{\mathrm{std}},\ p_{\mathrm{std}}\right) = q_{sp,\mathrm{std}}\cdot\rho_{\mathrm{std}} = 10{,}000\frac{\mathrm{ft}^3}{\mathrm{min}}\cdot 0.07497\frac{\mathrm{lbm}}{\mathrm{ft}^3} = 749.7\frac{\mathrm{lbm}}{\mathrm{min}}$$

I-2.8 Mass Flow of Dry Air

This is the mass flow of dry air included in the specified standard volumetric flow rate. It is specified to be delivered at the specified condition.

$$q_{m,\mathrm{mix}} = q_{m,da} + q_{m,vp} = q_{m,da} + q_{m,da}\cdot\left(\frac{\mathrm{mass}_{vp}}{\mathrm{mass}_{da}}\right)_{\mathrm{mix}} = q_{m,da} + q_{m,da}\cdot \mathrm{HR}_{\mathrm{mix}} = q_{m,da}\cdot(1 + \mathrm{HR}_{\mathrm{mix}})$$

Rearranging (and expressing as function)

$$q_{m,da}(q,\ T[°\mathrm{R}],\ T,\ \mathrm{RH},\ p) = \frac{q_{m,\mathrm{mix}}[q,\ T[°\mathrm{R}],\ T,\ \mathrm{RH},\ p)}{1 + \mathrm{HR}_{\mathrm{mix}}(T[°\mathrm{R}],\ \mathrm{RH},\ p)}$$

For the standard condition (in which volumetric flow rate is specified)

$$q_{m,da,\mathrm{std}} = q_{m,da}\left(q_{\mathrm{std}},\ T_{\mathrm{std}},\ \mathrm{RH}_{\mathrm{std}},\ p_{\mathrm{std}}\right) = \frac{q_{m,\mathrm{mix,std}}}{(1 + \mathrm{HR}_{\mathrm{mix,std}})} = \frac{749.7\frac{\mathrm{lbm}}{\mathrm{min}}}{1 + 0.00521} = 745.8\frac{\mathrm{lbm}}{\mathrm{min}}$$

I-2.9 Mass Flow of Mixture at Specified Conditions

This is the mass flow of the mixture at specified conditions that delivers the specified mass flow of dry air.

(a) $q_{m,da,sp} = q_{m,\mathrm{air,std}}$. (Fundamental equality for converting standard volumetric flow rate to volumetric flow rate at specified condition.)

$$q_{m,\mathrm{mix}} = q_{m,da} + q_{m,vp} = q_{m,da} + q_{m,da} \cdot \left(\frac{\mathrm{mass}_{vp}}{\mathrm{mass}_{da}}\right)_{\mathrm{mix}} = q_{m,da} + q_{m,da} \cdot \mathrm{HR}_{\mathrm{mix}} = q_{m,da} \cdot (1 + \mathrm{HR}_{\mathrm{mix}})$$

$$q_{m,\mathrm{mix}}(q, T[°\mathrm{R}], T, \mathrm{RH}, p) = q_{m,da}(q, T[°\mathrm{R}], T, \mathrm{RH}, p) \cdot [1 + HR_{\mathrm{mix}}(T[°\mathrm{R}], \mathrm{RH}, p)]$$

(b) Specified Condition

$$q_{m,\mathrm{mix},sp} = q_{m,\mathrm{mix}}\left(q_{\mathrm{std}}, T_{i,sp}, T_{i,sp}, \mathrm{RH}_{sp}, p_{i,sp}\right) = q_{m,da,\mathrm{std}} \cdot \left(1 + \mathrm{HR}_{\mathrm{mix},sp}\right)$$
$$= 745.8\frac{\mathrm{lbm}}{\mathrm{min}} \cdot (1 + 0.0014) = 746.8\frac{\mathrm{lbm}}{\mathrm{min}}$$

I-2.10 Volumetric Flow Rate of Mixture

This is the volumetric flow rate of the mixture at specified conditions.

$$q\left(q_m, T[°\mathrm{R}], T, \mathrm{RH}, p\right) = \frac{q_m}{\rho(T[°\mathrm{R}], T, \mathrm{RH}, p)}$$

(a) For the specified condition:

$$q_{sp} = q\left(q_{m,\mathrm{mix},sp}, T_{i,sp}, \mathrm{RH}_{sp}, p_{i,sp}\right) = \frac{q_{m,\mathrm{mix},sp}}{\rho_{i,sp}} = \frac{746.8\frac{\mathrm{lbm}}{\mathrm{min}}}{0.07287\frac{\mathrm{lbm}}{\mathrm{ft}^3}} = 10{,}248\frac{\mathrm{ft}^3}{\mathrm{min}}$$

II-3 A SIMPLIFIED EQUATION

The following equation is an algebraic reduction of the procedure rigorously demonstrated herein where the volume of a humid air mixture containing a quantity of dry air at one set of conditions can be converted to a volume of a humid air mixture at different conditions that contains the same quantity of dry air.

$$q_{sp}\left(q_{sp,\mathrm{std}}, T_{\mathrm{abs,std}}, T_{\mathrm{abs},sp}, T_{\mathrm{std}}[°\mathrm{F}], T_{sp}[°\mathrm{F}], p_{\mathrm{std}}, p_{sp}, \mathrm{RH}_{\mathrm{std}}, \mathrm{RH}_{sp}\right) = q_{sp,\mathrm{std}} \cdot \left(\frac{p_{\mathrm{std}} - p_{vp}(T_{\mathrm{std}}[°\mathrm{F}], \mathrm{RH}_{\mathrm{std}})}{p_{sp} - p_{vp}\left(T_{sp}[°\mathrm{F}], \mathrm{RH}_{sp}\right)}\right) \cdot \left(\frac{T_{\mathrm{abs},sp}}{T_{\mathrm{abs,std}}}\right)$$

For the example given:

$$q_{sp}\left(q_{\mathrm{std}}, T_{\mathrm{std}}, T_{i,sp}, T_{\mathrm{std}}, T_{i,sp}, p_{\mathrm{std}}, p_{i,sp}, \mathrm{RH}_{\mathrm{std}}, \mathrm{RH}_{sp}\right) = q_{\mathrm{std}} \cdot \left(\frac{p_{\mathrm{std}} - p_{vp,\mathrm{std}}}{p_{i,sp} - p_{vp,sp}}\right) \cdot \left(\frac{T_{i,sp}}{T_{\mathrm{std}}}\right)$$
$$= 10{,}000\frac{\mathrm{ft}^3}{\mathrm{min}} \cdot \left[\frac{(14.700 - 0.1220)\frac{\mathrm{lbf}}{\mathrm{in.}^2}\mathrm{abs}}{(13.500 - 0.0304)\frac{\mathrm{lbf}}{\mathrm{in.}^2}\mathrm{abs}}\right] = 10{,}248\frac{\mathrm{ft}^3}{\mathrm{min}}$$

This achieves the same result, but the rigorous demonstration offers a better sense of what the simplified equation is doing.

Nonmandatory Appendix A
Sample Uncertainty Calculations

A-1 INTRODUCTION

This Appendix shows the uncertainty calculation procedures for power measurement and for the thermodynamics of isentropic head and volumetric flow rate.

A-2 POWER MEASUREMENT

This uncertainty calculation and example for power measurement is based on the equations presented in Section 7. These calculations shall demonstrate the methodology for reference information.

Table A-2-1 tabulates the parameters necessary to obtain the uncertainty results for the instrumentation typically used for power measurement. Table A-2-2 is completed with expected or assumed values of systematic and random uncertainties based on the specific instrumentation to be used. Reference subsection 4-2 for details on power measurement instruments and methods.

A-3 ISENTROPIC HEAD AND VOLUMETRIC FLOW RATE

The procedures for the uncertainty calculations for the thermodynamics of isentropic head and volumetric flow rate shall be described separately to review each process in detail. These methods shall be worked as exhaustive calculations and as examples of the contributions of the components into the respective uncertainty and sensitivity contribution. The respective differential equations for the sensitivity coefficients are shown in detail for reference; however, the collection of values in detail are not specifically provided because of the brevity of this Section.

A-3.1 Isentropic Head Uncertainty Method

(a) Isentropic Head [repeated from eq. (5-3-5) for reference]

$$W_s = \left(\frac{\kappa_{\text{mix}}}{\kappa_{\text{mix}} - 1}\right) R_{i,\text{mix}} T_{i,\text{tot}} \left[\left(\frac{p_{d,\text{tot}}}{p_{i,\text{tot}}}\right)^{\frac{\kappa_{\text{mix}}-1}{\kappa_{\text{mix}}}} - 1\right] \tag{A-3-1}$$

(b) Functional Equation of Isentropic Head

$$W_s = f\left(\kappa_{\text{mix}},\ R_g,\ T_{i,\text{tot}},\ p_{i,\text{tot}},\ p_{d,\text{tot}}\right) \tag{A-3-2}$$

(c) Sensitivity Function for Isentropic Head

$$dW_s = \frac{\partial W_s}{\partial \kappa} d\kappa + \frac{\partial W_s}{\partial R_g} dR_g + \frac{\partial W_s}{\partial T_i} dT_i + \frac{\partial W_s}{\partial p_i} dp_i + \frac{\partial W_s}{\partial p_d} dp_d \tag{A-3-3}$$

Table A-3.1-1 outlines the independent parameters for each pressure and temperature measurement in the isentropic head uncertainty calculation example. Substituting X_i for the partial differential (sensitivity contribution) in the equation

$$\frac{dW_s}{d} = X_\kappa \frac{d\kappa}{\kappa} + X_{R_g} \frac{dR_g}{R_g} + X_T \frac{dT}{T} + X_{p_i} \frac{dp_i}{p_i} + X_{p_d} \frac{dp_d}{p_d} \tag{A-3-4}$$

results in the sensitivity equations for isentropic head, $\partial W_s/\partial X_i$, as put forth in Table A-3.1-2. Table A-3.1-3 summarizes the relative uncertainties in the calculation example.

Table A-2-1 Power Measurement Data

Parameter, Symbol, Units	Measured by	Nominal Value	Bias, % of Reading, $B_{\bar{x}_i}$	System Std. Uncertainty, % of Reading, $b_{\bar{x}_i}$ [Note (1)]	Random Std. Uncertainty, % of Reading, $s_{\bar{x}_i}$	Sensitivity, θ_i [Note (2)]	System Std. Uncertainty Contribution, $(b_{\bar{x}_i}\theta_i)^2$	Random Std. Uncertainty Contribution, $(s_{\bar{x}_i}\theta_i)^2$
Main Driver								
Power, P, kW	Power analyzer	234.0	0.3000	0.1500	0.0637	1	0.0225	0.0041
Voltage, V, volts	Potential transformer (PT)	488.6	0.3500	0.1750	0.0637	1	0.0306	0.0041
Current, I, amperes (A)	Current transformer (CT)	294.5	0.3500	0.1750	0.0637	1	0.0306	0.0041
Main driver						SUM	0.0838	0.1220
Auxiliary Power								
Power, P, kW	Auxiliary power analyzer	1.6	1.000	0.5000	0.1257	1	0.2500	0.0158
Voltage, V, volts	Potential transformer (PT)	487.0	1.200	0.6000	0.1257	1	0.3600	0.0158
Current, I, amperes (A)	Amp meter	5.0	1.000	0.5000	0.1257	1	0.2500	0.0158
	Current transformer (CT)		5.000	2.500	0.1257	1	6.250	0.0158
Power factor, *pf*		0.4	0.1000	0.0500	0.0000	1.176	0.0035	0.0000
Aux. power						SUM	7.113	0.0632
Net Power								
Main driver	SUM	234.0	...	0.3097	0.0000	0.95	0.0866	0.0000
Aux. power	SUM	1.6	...	2.679	0.0000	0.05	0.0179	0.0000
Net power	SUM	235.6				SUM	0.1045	0.0000

NOTES:

(1) Each bias is assumed to have a 95% confidence level, normal distribution, and degrees of freedom >30.

(2) These sensitivities are assumed for this example; every test will have its own set, depending on the characteristics of the equipment being tested.

Table A-2-2 Summary Results of Power Measurements

Description	Calculated Power, kW	Systematic Standard Uncertainty, % of Reading, b_R	Random Standard Uncertainty, % of Reading, s_R	Combined Standard Uncertainty, % of Reading, u_R	Expanded Uncertainty, % of Reading, $U_{R,95}$
Main driver	234.0	0.2894	0.1103	0.3097	0.6194
Auxiliary power	1.6	2.667	0.2514	2.679	5.358
Net power	235.6	0.3233	0.0000	0.3233	0.6466

Table A-3.1-1 Independent Parameters for Isentropic Head Uncertainty Calculation Example

Parameter, Symbol, X_i, Units	Nominal Value	Absolute Systematic Standard Uncertainty, $b_{\bar{x}_i}$	Absolute Random Standard Uncertainty, $s_{\bar{x}_i}$	Absolute Sensitivity, θ_i	Absolute Systematic Standard Uncertainty Contribution, $(b_{\bar{x}_i}\theta_i)^2$	Absolute Random Standard Uncertainty Contribution, $(s_{\bar{x}_i}\theta_i)^2$
Ratio of specific heat, $\kappa_{i_{mix}}$	1.3967	0.0000	0.0000	0.2453	0.0000	0.0000
Gas constant of the mixture, $R_{i,\text{mix}}$, $\frac{\text{ft} \cdot \text{lbf}}{\text{lbm} \cdot {}^\circ\text{R}}$	54.029	0.0000	0.0000	1.0000	0.0000	0.0000
Total inlet temperature, $T_{i,\text{tot}}$, °R	543.296	0.0943	0.0723	1.0000	8.8925 E−3	5.2273 E−3
Total inlet pressure, $p_{i,\text{tot}}$, psia	14.117	0.0141	0.0102	−1.6516	5.4230 E−4	2.8379 E−4
Total discharge pressure, $p_{d,\text{tot}}$, psia	27.434	0.0247	0.0201	1.6516	1.6642 E−3	1.1020 E−3

GENERAL NOTES:
(a) Quantity of four instruments for each pressure and temperature measurement.
(b) Systematic standard uncertainty considers instrument to DAQ system string (i.e., accuracy, full-scale, current conversion, nonlinearity, repeatability, module error, drift).

A-3.2 Volumetric Flow Rate Uncertainty Method

(a) Equation for Mass Flow [eq. (4-5-1) repeated from subsection 4-5.6 for reference]

$$q_m = n\frac{\pi}{4}d^2C_d\varepsilon\sqrt{\frac{2\rho_1(\Delta p)g_c}{1 - \beta^4}} \tag{A-3-5}$$

$$q_m = 0.52052\frac{\pi}{4}d^2C_d\varepsilon\sqrt{\frac{2\rho\Delta p(g_c)}{1 - \beta^4}} \tag{A-3-6}$$

where

$$d(\text{in.}),\ \rho\left(\frac{\text{lbm}}{\text{ft}^3}\right),\ \Delta p(\text{psi}),\ \rho = \frac{p}{R_{i,\text{mix}}{}^*T}$$

(b) Sensitivity Function for Mass Flow

$$dq_m = \frac{\partial q_m}{\partial C_d}dC_d + \frac{\partial q_m}{\partial d}dd + \frac{\partial q_m}{\partial D}dD + \frac{\partial q_m}{\partial p}dp + \frac{\partial q_m}{\partial T}dT + \frac{\partial q_m}{\Delta p}d\Delta p \tag{A-3-7}$$

Table A-3.1-2 Equations of Sensitivity Contribution for Isentropic Head

Symbol, X_i	Nominal Value	Formula for Absolute Sensitivity ($\partial W_s/\partial X_i$)
$\kappa_{i,mix}$	1.3967	$\dfrac{R_{i,mix} \cdot T_{i,tot}\left[\left(\dfrac{p_{d,tot}}{p_{i,tot}}\right)^{\frac{\kappa_{i,mix}-1}{\kappa_{i,mix}}}-1\right]}{\kappa_{i,mix}-1} - \dfrac{R_{i,mix} \cdot T_{i,tot} \cdot \kappa_{i,mix}\left[\left(\dfrac{p_{d,tot}}{p_{i,tot}}\right)^{\frac{\kappa_{i,mix}-1}{\kappa_{i,mix}}}-1\right]}{(\kappa_{i,mix}-1)^2} + \dfrac{R_{i,mix} \cdot T_{i,tot} \cdot \kappa_{i,mix} \cdot \ln\left(\dfrac{p_{d,tot}}{p_{i,tot}}\right) \cdot \left(\dfrac{p_{d,tot}}{p_{i,tot}}\right)^{\frac{\kappa_{i,mix}-1}{\kappa_{i,mix}}} \cdot \left(\dfrac{1}{\kappa_{i,mix}} - \dfrac{\kappa_{i,mix}-1}{\kappa_{i,mix}^2}\right)}{\kappa_{i,mix}-1}$
$R_{i,mix}$	54.029	$\dfrac{T_{i,tot} \cdot \kappa_{i,mix}\left[\left(\dfrac{p_{d,tot}}{p_{i,tot}}\right)^{\frac{\kappa_{i,mix}-1}{\kappa_{i,mix}}}-1\right]}{\kappa_{i,mix}-1}$
$T_{i,tot}$	543.296	$\dfrac{R_{i,mix} \cdot \kappa_{i,mix}\left[\left(\dfrac{p_{d,tot}}{p_{i,tot}}\right)^{\frac{\kappa_{i,mix}-1}{\kappa_{i,mix}}}-1\right]}{\kappa_{i,mix}-1}$
$p_{i,tot}$	14.117	$\dfrac{R_{i,mix} \cdot T_{i,tot} \cdot p_{d,tot} \cdot \left(\dfrac{p_{d,tot}}{p_{i,tot}}\right)^{\frac{\kappa_{i,mix}-1}{\kappa_{i,mix}}-1}}{p_{i,tot}^{2}}$
$p_{d,tot}$	27.434	$\dfrac{R_{i,mix} \cdot T_{i,tot} \cdot \left(\dfrac{p_{d,tot}}{p_{i,tot}}\right)^{\frac{\kappa_{i,mix}-1}{\kappa_{i,mix}}-1}}{p_{i,tot}}$

Table A-3.1-3 Summary of Relative Uncertainties

Parameter, Symbol, Units	Calculated Value	Absolute Systematic Uncertainty, b_R	Absolute Random Standard Uncertainty, s_R	Combined Uncertainty of the Result, u_R	Total Absolute Uncertainty, $U_{R,95}$
Isentropic work, W_s, ft·lbf/lbm	21464.3	0.105	0.081	0.133	0.266
		Net Uncertainty $\left(\frac{U_{R,95}}{W_s}\right)$			1.24×10^{-3} %

As shown in Table A-3.2-1, substituting X_i for the partial differential (sensitivity contribution) in the following equation results in the sensitivity equations for mass flow $\left(\frac{\partial q_m}{\partial X_i}\right)$. The unit conversion of 0.52502 follows the units detailed therein.

Table A-3.2-2 outlines the independent parameters for each pressure and temperature measurement in the volumetric flow rate uncertainty calculation example. Table A-3.2-3 summarizes the relative uncertainties in the calculation example.

A-4 SYSTEMATIC AND RANDOM STANDARD UNCERTAINTY EXAMPLES

This section evaluates the uncertainty derived from the instrumentation measurement and the reading and accuracy of the DAQ. Table A-4-1 provides the systematic standard uncertainty values used for this example; the instrumentation and data acquisition path should be evaluated carefully per application. Table A-4-2 details the random uncertainty values for the same parameter.

Table A-3.2-1 Equations of Sensitivity Contribution

Symbol, X_i	Nominal Value	Formula for Absolute Sensitivity, $\partial q_m/\partial X_i$
C_d	0.6047	$\dfrac{0.5250 \cdot \varepsilon \cdot d^2 \cdot \sqrt{\rho \cdot \Delta p}}{\sqrt{1-\dfrac{d^4}{D^4}}}$
d	9.9002	$\dfrac{1.05004 \cdot C_d \cdot \varepsilon \cdot d \cdot \sqrt{\rho \cdot \Delta p}}{\sqrt{1-\dfrac{d^4}{D^4}}} + \dfrac{1.05004 \cdot C_d \cdot \varepsilon \cdot d^5 \cdot \sqrt{\rho \cdot \Delta p}}{D^4 \cdot \left(1-\dfrac{d^4}{D^4}\right)^{\frac{3}{2}}}$
D	18.001	$-\left[\dfrac{1.050 \cdot C_d \cdot \varepsilon \cdot d^6 \cdot \sqrt{\rho \cdot \Delta p}}{D^5 \cdot \left(1-\dfrac{d^4}{D^4}\right)^{3/2}}\right]$
p	27.34	$\dfrac{0.26251 \cdot C_d \cdot \varepsilon \cdot d^2 \cdot \Delta p}{\mathrm{R} \cdot \mathrm{T} \cdot \sqrt{1-\dfrac{d^4}{D^4}} \cdot \sqrt{\dfrac{\Delta p \cdot p}{\mathrm{R} \cdot \mathrm{T}}}}$ dp is Δp, 0.2625
T	678.43°R	$-\left(\dfrac{0.26251 \cdot C_d \cdot \varepsilon \cdot d^2 \cdot \Delta p \cdot p}{\mathrm{R} \cdot \mathrm{T}^2 \cdot \sqrt{1-\dfrac{d^4}{D^4}} \cdot \sqrt{\dfrac{\Delta p \cdot p}{\mathrm{R} \cdot \mathrm{T}}}}\right)$
Δp	3.592	$\dfrac{0.2625 \cdot \varepsilon \cdot \rho \cdot C_d \cdot d^2}{\sqrt{\rho \cdot \Delta p} \cdot \sqrt{1-\dfrac{d^4}{D^4}}}$

Table A-3.2-2 Independent Parameters for Volumetric Flow Rate Uncertainty Calculation Example

Parameter, Symbol, X_i, Units	Nominal Value	Absolute Systematic Standard Uncertainty, $b_{\bar{x}_i}$	Absolute Random Standard Uncertainty, $s_{\bar{x}_i}$	Absolute Sensitivity θ_i	Absolute Systematic Standard Uncertainty Contribution, $(b_{\bar{x}_i}\theta_i)^2$	Absolute Systematic Standard Uncertainty Contribution, $(s_{\bar{x}_i}\theta_i)^2$
Discharge coefficient, C_d	0.6047	0	0	32.2602	0	0
Orifice bore diameter, d, in.	9.9002	0.0005	0	4.3378	4.7042 E−6	0
Piping bore diameter, D, in.	18.001	0.001	0	−0.2183	4.7645 E−8	0
Pressure upstream orifice, p, psi	27.34	0.02464	0.0216	0.0297	5.3661 E−7	4.1237 E−7
Temperature upstream orifice, T, °F	218.759	0.24657	0.0883	−0.0012	8.7271 E−8	1.1192 E−8
Differential pressure, Δp, psid	3.592	0.005730	0.0041	2.7155	2.421 E−4	1.2395 E−4

GENERAL NOTES:
(a) Four instruments used for each pressure and temperature measurement.

Table A-3.2-3 Summary of Relative Uncertainties

Parameter, Symbol, Unit	Calculated Value	Absolute Systematic Uncertainty, b_R	Absolute Random Standard Uncertainty, S_R	Combined Uncertainty of the Result, u_R	Total Absolute Uncertainty, $U_{R,95}$
Mass flow rate, q_m, lbm/sec	19.508	0.016	0.011	0.019	0.039
Net Uncertainty $\left(\frac{U_{R,95}}{q_m}\right)$					**0.19%**

GENERAL NOTE: For this example, the calibrated instrumentation accuracies are
(a) Upstream temperature: ±0.08%.
(b) Upstream pressure: ±0.21%.
(c) Differential pressure: ±0.20%.

Table A-4-1 Systematic Standard Uncertainty Component of a Parameter

Example: Flow Measurement Upstream Pressure				
Data Acquisition Component, Units		**Nominal Value**		
Instrument range, psi		30.00		
Average reading of N measurements, psi		27.341		
DAQ temperature at time of reading, °C		25.05		
Analog Input Technical Specifications				
Uncertainty Component	**Accuracy (acc), %**	**Calculation**	**Result**	**(Result)^2**
Current: full scale @ 25°C (77°F)	0.350	= acc · (27.341/30.00)	0.00319	1.02 E−05
Current: ±0.0045% per °C	0.0045	= acc · 25.05	0.001125	1.27 E−06
Nonlinearity	0.030	= acc · 27.341	0.008202	6.73 E−05
Repeatability	0.030	= acc · 27.341	0.008202	6.73 E−05
Current (A)	0.500	= acc · 0.016 · 30	0.0024	5.76 E−06
Systematic standard uncertainty: flow measurement upstream pressure (Sum)			$b_{\bar{x}_i}$	**0.02464**

GENERAL NOTE: Values used in this table are amps (A) for unit consistency.

Table A-4-2 Random Standard Uncertainty of the Mean of *N* Measurements

Example: Flow Measurement Upstream Pressure		
Data Acquisition Component, Units		**Nominal Value**
Instrument range, psi		30.00
Average reading of *N* measurements, psi		27.341
Reading min., psi		27.311
Reading max., psi		27.373
Number of instruments		4
	Sum[$(Xj\text{-}X_{avg})^2/(N-1)$]	0.000465
Delta, psi	(Max.–Min.)	0.062
Accuracy	(Delta/Range)	0.21%
Random standard uncertainty, psi	$s_{\bar{x}_i}$	**0.02156**

Nonmandatory Appendix B
Sample Calculation: Dynamic Blowers

B-1 INTRODUCTION

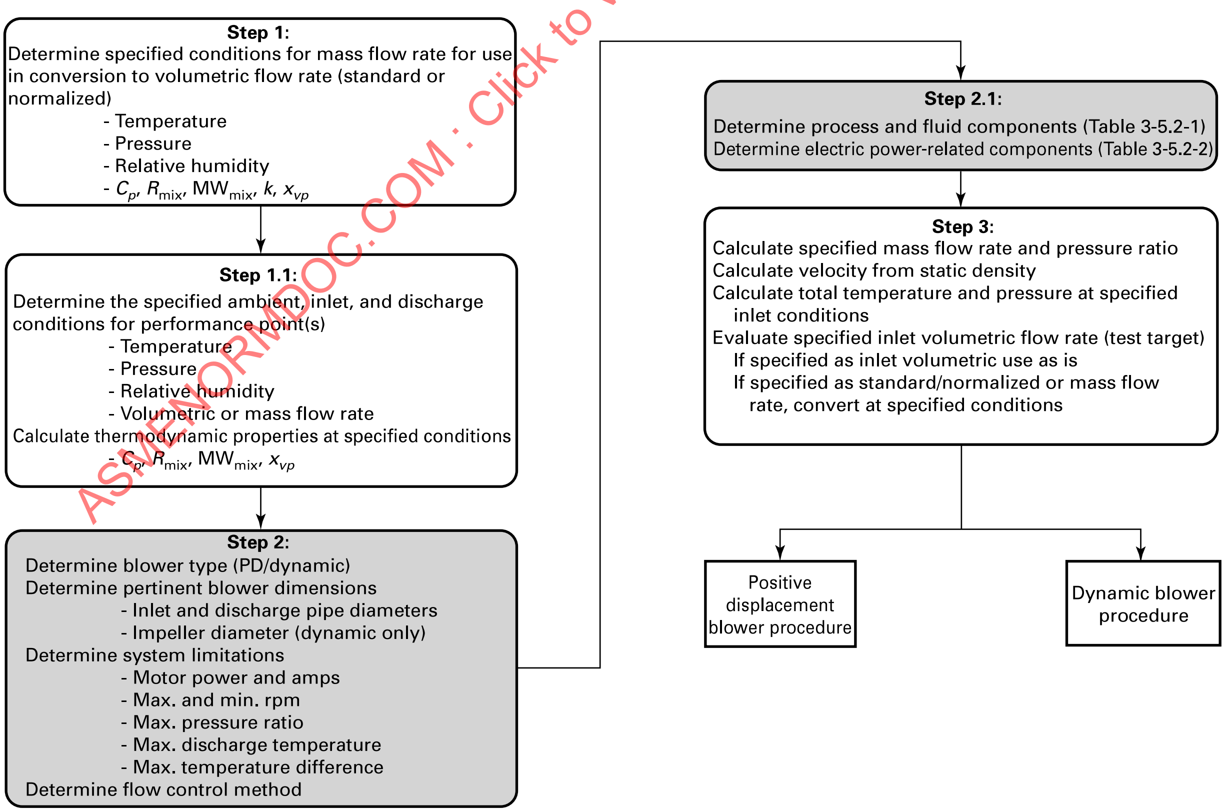
This Appendix uses a simple formula for conversion of standard conditions to site conditions for dynamic blowers. The first steps of the calculation procedure are illustrated in Figure B-1-1. A rigorous calculation for conversion from standard to specified conditions is found in Mandatory Appendix I and best illustrates the principles of conversion between conditions. In the example in this Appendix, speed is a variable of the blower configuration, and it follows the permissible deviations of similitude parameters established in para. 3-5.4.

B-2 STEP 1: DETERMINE CONDITIONS

B-2.1 Reference Standard Air Conditions

The first step shall be to determine specified conditions for mass flow rate for use in conversion to volumetric flow rate (standard or normalized). For the purpose of this example, the reference air conditions are

Figure B-1-1 Preliminary Steps



Condition	Value
Temperature, T_{std}	68.0°F
Pressure, p_{std}	$14.700 \cdot \frac{lbf}{in.^2}$ abs
Relative humidity, RH_{std}	36%

B-2.2 Specified Condition

It is then necessary to determine the specified ambient, inlet, and discharge conditions for performance points, and to calculate the thermodynamic properties at the specified conditions. For the purpose of this example, the specified conditions are

Condition	Value
Volumetric flow rate, $q_{sp,std}$	10,000 SCFM (ft^3/min at standard condition)
Inlet temperature, $T_{i,sp}$	40.0°F
Barometric pressure, $p_{a,sp}$	$13.950 \frac{lbf}{in.^2}$ abs
Inlet pressure, $p_{i,sp}$	$13.500 \frac{lbf}{in.^2}$ abs (measured in zero velocity plenum room)
Discharge pressure, $p_{d,sp}$	$8.90 \frac{lbf}{in.^2}$ gauge (total pressure)
Relative humidity, RH_{sp}	25%
Estimated dirty filter loss, Δp_1	$0.35 \frac{lbf}{in.^2}$

B-2.2.1 Account for Dirty Filter Loss. Adjust the specified inlet pressure to account for estimated dirty filter loss using the allowance

$$p_{i,sp,\text{adj}} = p_{i,sp} - \Delta p_1 = 13.500 \frac{\text{lbf}}{\text{in.}^2}\text{abs} - 0.350\frac{\text{lbf}}{\text{in.}^2}$$
$$= 13.150\frac{\text{lbf}}{\text{in.}^2}\text{abs}$$

B-2.2.2 Test Condition. In this example, room inlet and zero velocity are used. The discharge pressure and temperature are measured in an 18-in diameter duct. The test conditions are

Condition	Value
Inlet temperature, $T_{i,t}$	65.1°F
Ambient pressure, $p_{a,t}$	$14.300 \frac{lbf}{in.^2}$ abs
Relative humidity, RH_t	50%
Inlet pressure, $p_{i,t}$	$14.150 \frac{lbf}{in.^2}$ abs

B-3 STEP 2: DETERMINE BLOWER TYPE, DIMENSIONS, AND LIMITATIONS

The blower type — PD or dynamic — shall be determined, as well as the pertinent dimensions: inlet and discharge pipe diameters and, for dynamic blowers, impeller diameter. The flow control method shall be ascertained. The system limitations to be ascertained are

(a) motor power and amps
(b) maximum and minimum rpm
(c) maximum pressure ratio
(d) maximum discharge temperature
(e) maximum temperature difference

Using Tables 3-5.2-1 and 3-5.2-2 as checklists, the process and fluid components and the electric power-related components of the blower being tested shall be identified.

B-4 STEP 3: ESTIMATE OPERATING CONDITION TARGETS FOR TEST

B-4.1 Calculate Specified Volumetric Flow Rate and Pressure Ratio

Determine the volumetric flow rate for specified conditions. The specified inlet volumetric flow rate is stated for standard air condition and, as such, is often considered as a specified mass flow rate. This value shall be converted to a volumetric flow rate for air at specified conditions. The following example is an abbreviated method of determination.

B-4.1.1 Saturated Vapor-Pressure Beta Coefficients. The empirical function is based on T in Rankine units.

$$\beta_{sv} = \frac{-7202.2367}{T(°\mathrm{R}) - 70.431}$$

NOTE: T (°R) is used to refer to a function argument for temperature expressed exclusively in degrees Rankine for this empirical function that leads to determination of saturated vapor pressure in air. Other functions may use t_{abs} as a function argument for temperature expressed in absolute scale using units that correspond to the units system being used for the calculations.

(a) Standard Condition

$$\beta_{sv,\mathrm{std}} = \beta_{sv}(T_{\mathrm{std}}[°\mathrm{R}]) = \frac{-7,202.2367}{(68 + 459.67)\ °\mathrm{R} - 70.431} = -15.7516$$

(b) Specified Condition

$$\beta_{sv,sp} = \beta_{sv}\left(T_{i,sp}[°\mathrm{R}]\right) = \frac{-7,202.2367}{(40 + 459.67)°\mathrm{R} - 70.431} = -16.7791$$

B-4.1.2 Saturated Vapor Pressures. The empirical function based on the beta coefficient.

$$p_{sv}(T[°\mathrm{R}]) = 2.34908 \cdot 10^6 \cdot e^{\beta_{sv}(T[°\mathrm{R}])} \frac{\mathrm{lbf}}{\mathrm{in.}^2}\mathrm{abs}$$

(a) Standard Condition

$$p_{sv,\mathrm{std}} = p_{sv}(T_{\mathrm{std}}[°\mathrm{R}]) = 2.34908 \cdot 10^6 \cdot e^{-15.7516} = 0.3389 \frac{\mathrm{lbf}}{\mathrm{in.}^2}\mathrm{abs}$$

(b) Specified Condition

$$p_{sv,sp} = p_{sv}\left(T_{i,sp}[°\mathrm{R}]\right) = 2.34908 \cdot 10^6 \cdot e^{-16.7791} = 0.1213 \frac{\mathrm{lbf}}{\mathrm{in.}^2}\mathrm{abs}$$

B-4.1.3 Air Mixture Vapor Pressures. This function is based on saturated vapor pressure and relative humidity.

$$p_{vp}(T[°\mathrm{R}],\mathrm{RH}) = p_{sv}(T[°\mathrm{R}]) \cdot \mathrm{RH}$$

(a) Standard Condition

$$p_{vp,\mathrm{std}} = p_{vp}(T_{\mathrm{std}}[°\mathrm{R}], \mathrm{RH}_{\mathrm{std}}) = p_{sv}(T_{\mathrm{std}}[°\mathrm{R}]) \cdot \mathrm{RH}_{\mathrm{std}} = 0.3389 \frac{\mathrm{lbf}}{\mathrm{in.}^2}\mathrm{abs} \cdot 0.36 = 0.1220 \frac{\mathrm{lbf}}{\mathrm{in.}^2}\mathrm{abs}$$

(b) Specified Condition

$$p_{vp,sp} = p_{vp}\left(T_{i,sp}[°\mathrm{R}], \mathrm{RH}_{sp}\right) = p_{sv}\left(T_{i,sp}[°\mathrm{R}]\right) \cdot \mathrm{RH}_{sp} = 0.1213 \frac{\mathrm{lbf}}{\mathrm{in.}^2}\mathrm{abs} \cdot 0.25 = 0.0303 \frac{\mathrm{lbf}}{\mathrm{in.}^2}\mathrm{abs}$$

B-4.1.4 Air Mixture Volumetric Flow Rate at Specified Condition. The function used here is a shortcut. See Mandatory Appendix I for a rigorous method to determine the volumetric flow rate at specified condition from the volume capacity at standard condition.

$$q_{v,sp}\left(q_{v,\mathrm{std}}, T_{\mathrm{std}}, T_{sp}, T_{\mathrm{std}}[°\mathrm{R}], T_{sp}[°\mathrm{R}], p_{\mathrm{std}}, p_{sp}, \mathrm{RH}_{\mathrm{std}}, \mathrm{RH}_{sp}\right) = q_{v,\mathrm{std}} \cdot \left[\frac{p_{\mathrm{std}} - p_{vp}(T_{\mathrm{std}}[°\mathrm{R}], \mathrm{RH}_{\mathrm{std}})}{p_{sp} - p_{vp}\left(T_{sp}[°\mathrm{R}], \mathrm{RH}_{sp}\right)}\right] \cdot \left(\frac{T_{sp}}{T_{\mathrm{std}}}\right)$$

(a) Specified Condition

$$q_{v,sp} = q_{v,sp}\left(q_{v,\text{std}}, T_{\text{std}}, T_{i,sp}, T_{\text{std}}[°\text{F}], T_{i,sp}[°\text{F}], p_{\text{std}}, p_{i,sp,\text{adj}}, \text{RH}_{\text{std}}, \text{RH}_{sp}\right) = q_{v,\text{std}} \cdot \left(\frac{p_{\text{std}} - p_{vp,\text{std}}}{p_{i,sp} - p_{vp,sp}}\right) \cdot \left(\frac{T_{i,sp}}{T_{\text{std}}}\right)$$

$$= 10{,}000 \frac{\text{ft}^3}{\text{min}} \cdot \left[\frac{(14.700 - 0.1220)\dfrac{\text{lbf}}{\text{in.}^2}\text{abs}}{(13.150 - 0.0303)\dfrac{\text{lbf}}{\text{in.}^2}\text{abs}}\right] \cdot \left[\frac{(40 + 459.67)°\text{R}}{(68 + 459.67)°\text{R}}\right] = 10{,}522 \frac{\text{ft}^3}{\text{min}}$$

B-5 STEP 4: TEST PREPARATION

B-5.1 Verify Mechanical Readiness (as Applicable)

As illustrated in Figure B-5.1-1, the next step shall be to verify mechanical readiness for the test. Bearing and gear lubrication, belt tensioning system, and piping conditions shall be evaluated.

B-5.2 Verify Safety Considerations

Refer to para. 3-5.1 for a safety overview. Belt guards, mechanical systems, and wiring and electric systems shall be evaluated. Safety precautions shall be in place, and hearing and eye protection shall be provided.

B-5.3 Preliminary Test Runs

Preliminary test runs shall be performed as detailed in para. 3-2.2 and in accordance with test operation procedures explained in subsection 3-5. Instruments shall be configured per Section 4, and instrument calibration records verified per para. 4-1.2.

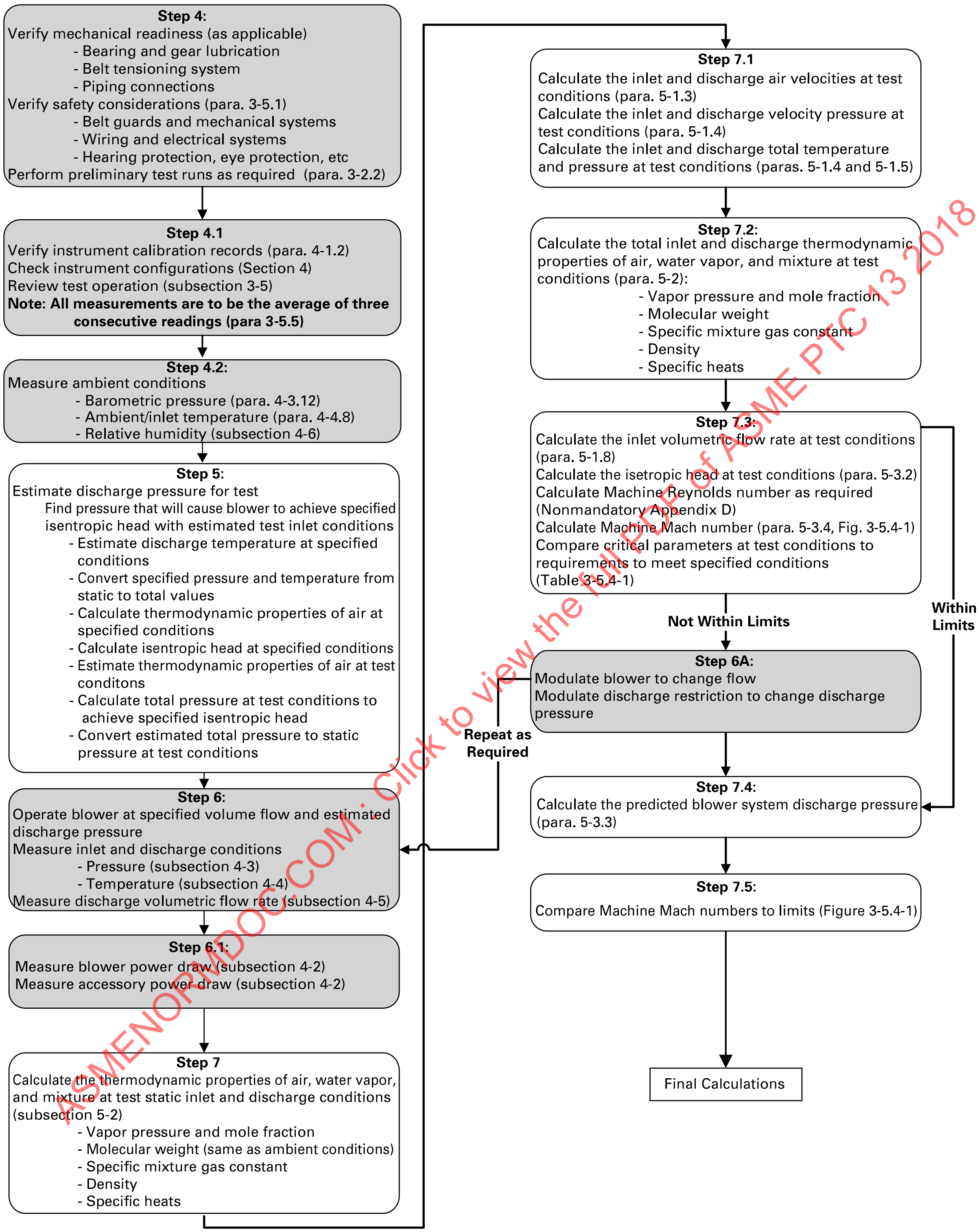
B-6 STEP 5: DETERMINE DISCHARGE PRESSURE FOR TEST

The discharge pressure for the test should be set with the isentropic head equal to the isentropic head at the specified condition. Data collection and computing systems at the test facility can enable this step with real-time measurements of atmospheric pressure, relative humidity, inlet pressure, inlet temperature, discharge pressure, discharge temperature, and mass flow. Real-time calculations can estimate air velocities at measurement points and make appropriate corrections for total pressure and total temperature. Additional real-time calculations provide instantaneous readout of the isentropic head of the operating blower. Adjustments of a discharge throttling valve change the discharge pressure, resulting in a real-time display of the corresponding isentropic head, in order that the blower operates at the specified isentropic head.

B-6.1 Calculate the Isentropic Head for Specified Condition

In the absence of such real-time calculations, or for an understanding of how test discharge pressures are determined, the calculations in this subsection provide a means of estimating the appropriate discharge pressure for the blower to operate at during the test.

Figure B-5.1-1 Dynamic Blower Test Calculations



B-6.1.1 Pressure Ratio

(a) Static Condition

$$r_p\left(p_i,\, p_{d,ga},\, p_a\right) = \frac{p_{d,ga} + p_a}{p_i}$$

(b) Specified Condition

$$r_{p,\text{static},sp} = r_p\left(p_{i,sp,\text{adj}},\, p_{d,sp},\, p_{a,sp}\right) = \frac{p_{d,sp} + p_{a,sp}}{p_{i,sp,\text{adj}}} = \frac{\left(8.90\frac{\text{lbf}}{\text{in.}^2} + 13.95\frac{\text{lbf}}{\text{in.}^2}\text{abs}\right)\frac{\text{lbf}}{\text{in.}^2}\text{abs}}{13.150\frac{\text{lbf}}{\text{in.}^2}\text{abs}} = 1.738$$

B-6.1.2 Air Mixture Molecular Weight at Specified Condition. The molecular weight of the air mixture is based on mole fraction proportions of dry air and water vapor in the mixture.

$$\text{MW}_{da} = 28.970\frac{\text{lbm}}{\text{lbmol}} \quad \text{MW}_{vp} = 18.015\frac{\text{lbm}}{\text{lbmol}}$$

x_{vp} = mole fraction of water vapor in mix = vapor pressure/total pressure

$$x_{vp}(T[°\text{R}],\, \text{RH},\, p) = \frac{p_{sv}(T[°\text{R}]) \cdot \text{RH}}{p_a} = \frac{p_{vp}(T[°\text{R}], \text{RH})}{p_a}$$

$$\text{MW}_{\text{mix}}\,(T[°\text{R}],\, \text{RH},\, p) = \text{MW}_{vp} \cdot x_{vp} \cdot (T[°\text{R}],\, \text{RH},\, p) + \text{MW}_{da} \cdot \left[1 - x_{vp} \cdot \left(T[°\text{R}],\, \text{RH},\, p\right)\right]$$

(a) Specified Condition

$$x_{vp,sp} = x_{vp}\left(T_{i,sp},\, \text{RH}_{sp},\, p_{i,sp,\text{adj}}\right) = \frac{p_{vp,sp}}{p_{i,sp,\text{adj}}} = \frac{0.0304\frac{\text{lbf}}{\text{in.}^2}\text{abs}}{13.150\frac{\text{lbf}}{\text{in.}^2}\text{abs}} = 0.0023$$

$$\text{MW}_{\text{mix},sp} = \text{MW}_{\text{mix}}\left(T_{i,sp},\, \text{RH}_{sp},\, p_{i,sp,\text{adj}}\right) = \text{MW}_{vp} \cdot x_{vp,sp} + \text{MW}_{da}\left(1 - x_{vp,sp}\right)$$

$$= 18.015\frac{\text{lbm}}{\text{lbmol}} \cdot 0.0023 + 28.970\frac{\text{lbm}}{\text{lbmol}} \cdot (1 - 0.0023) = 28.945\frac{\text{lbm}}{\text{lbmol}}$$

B-6.1.3 Air Mixture Density at Specified Condition. This is derived from the ideal gas law.

$$\bar{R} = 1{,}545.3488\frac{\text{ft} \cdot \text{lbf}}{\text{lbmol} \cdot °R}\text{Universal Gas Constant}$$

$$\rho(T[°\text{R}],\, T,\, \text{RH},\, p) = \frac{p}{\dfrac{\bar{R}}{\text{MW}_{\text{mix}}\,(T[°\text{R}], \text{RH}, p)} \cdot T}$$

NOTE: With MW_{mix} already determined, p and T can be used with any units consistent with the units for the chosen universal gas constant.

(a) Specified Condition

$$\rho_{i,sp} = \rho\left(T_{i,sp}[°\text{R}],\, \text{RH}_{sp},\, p_{i,sp,\text{adj}}\right) = \frac{p_{i,sp,\text{adj}}}{\dfrac{\bar{R}}{\text{MW}_{\text{mix},sp}} \cdot T_{i,sp}} = \frac{13.150\frac{\text{lbf}}{\text{in.}^2} \cdot \frac{144\,\text{in.}^2}{\text{ft}^2}}{\dfrac{1,545.3488\frac{\text{ft} \cdot \text{lbf}}{\text{lbmol} \cdot °\text{R}}}{28.945\frac{\text{lbm}}{\text{lbmol}}} \cdot (40 + 459.67)\,°\text{R}} = 0.0710\frac{\text{lbm}}{\text{ft}^3}$$

B-6.1.4 Mass Flow of Mixture.

$$q_{m,sp}\left(q_v,\, T[°\text{R}],\, T,\, \text{RH},\, p\right) = q_v \cdot \rho(T[°\text{R}],\, T,\, \text{RH},\, p)$$

$$q_{m,sp}\left(q_{v,sp},\ T_{sp}[°\mathrm{R}],\ T_{sp},\ \mathrm{RH}_{sp},\ p_{i,sp,\mathrm{adj}}\right) = q_{v,sp}\cdot\rho_{i,sp} = 10{,}522\frac{\mathrm{ft}^3}{\mathrm{min}}\cdot 0.0710\frac{\mathrm{lbm}}{\mathrm{ft}^3} = 747.1\frac{\mathrm{lbm}}{\mathrm{min}}$$

B-6.1.5 Inlet Velocity at Specified Condition. These measurements are for total pressure and total temperature. See Nonmandatory Appendix C for an example of calculating total pressures and total temperatures in a piped inlet to a blower.

When inlet condition is room air, $V_{i,sp}$ = 0

The inlet condition is measured in room at zero velocity. $T_{i,\mathrm{tot},sp} = T_{i,sp}$ = (40 + 459.67) °R

B-6.1.6 Pressure Ratio (Total Pressures)

$$r_{p,\mathrm{tot},sp} = r_p\left(p_{i,sp},\ p_{d,sp}\right) = \frac{p_{d,sp}}{p_{i,sp}} = \frac{22.850\frac{\mathrm{lbf}}{\mathrm{in.}^2}\mathrm{abs}}{13.150\frac{\mathrm{lbf}}{\mathrm{in.}^2}\mathrm{abs}} = 1.738$$

B-6.1.7 Specific Heats

(a) Dry Air and Vapor. Calculate the molar specific heat of air and vapor using the empirical function of temperature. Calculate the specific heat of the air mix only at the inlet temperature; adjusting the specific heat for increasing temperature through the blower yields negligible improvements in accuracy.

$$\bar{c}_{p,da}(T[°\mathrm{R}]) = \left[3.64746 - \frac{0.708954}{10^3}\cdot T[°\mathrm{R}] + \frac{9.41274}{10^7}\cdot T[°\mathrm{R}]^2 - \frac{0.254338}{10^9}\cdot T[°\mathrm{R}]^3\right]\cdot\overline{R}$$

$$\bar{c}_{p,vp}(T[°\mathrm{R}]) = \left[4.05380 - \frac{0.51711}{10^3}\cdot T[°\mathrm{R}] + \frac{1.05975}{10^6}\cdot T[°\mathrm{R}]^2 - \frac{0.292781}{10^9}\cdot T[°\mathrm{R}]^3\right]\cdot\overline{R}$$

where $\overline{\mathrm{R}} = 1.98588\frac{\mathrm{Btu}}{\mathrm{lbmol}\cdot°\mathrm{R}}$

$$\bar{c}_{p,da,i,sp} = \bar{c}_{p,da}\left(T_{i,sp}[°\mathrm{R}]\right) = \bar{c}_{p,da}[(40 + 459.67)°\mathrm{R}] = 6.944\frac{\mathrm{Btu}}{\mathrm{lbmol}\cdot°\mathrm{R}}$$

$$\bar{c}_{p,vp,i,sp} = \bar{c}_{p,vp}\left(T_{i,sp}[°\mathrm{R}]\right) = \bar{c}_{p,vp}[(40 + 459.67)°\mathrm{R}] = 7.990\frac{\mathrm{Btu}}{\mathrm{lbmol}\cdot°\mathrm{R}}$$

(b) Specific Heat of the Air Mixture.

$$c_{p,\mathrm{mix}}\left(T[°\mathrm{R}],\ x_{vp},\ \mathrm{MW}_{\mathrm{mix}}\right) = \frac{\left(1 - x_{vp}\right)\cdot\bar{c}_{p,da}(T[°\mathrm{R}]) + x_{vp}\cdot\bar{c}_{p,vp}(T[°\mathrm{R}])}{\mathrm{MW}_{\mathrm{mix}}}$$

$$c_{p,\mathrm{mix},i,sp} = c_{p,\mathrm{mix}}\left(T_{i,sp}[°\mathrm{R}],\ x_{vp,sp},\ \mathrm{MW}_{\mathrm{mix},sp}\right) = \frac{\left(1 - x_{vp,sp}\right)\cdot\bar{c}_{p,da,i,sp} + x_{vp,sp}\cdot\bar{c}_{p,vp,i,sp}}{\mathrm{MW}_{\mathrm{mix},sp}}$$

$$= \frac{(1 - 0.0023)\cdot 6.944\frac{\mathrm{Btu}}{\mathrm{lbmol}\cdot°\mathrm{R}} + 0.0023\cdot 7.990\frac{\mathrm{Btu}}{\mathrm{lbmol}\cdot°\mathrm{R}}}{28.945\frac{\mathrm{lbm}}{\mathrm{lbmol}}} = 0.2400\frac{\mathrm{Btu}}{\mathrm{lbm}\cdot°\mathrm{R}}$$

(c) Ratio of Specific Heats of the Air Mixture

$$\kappa_{\text{mix},sp} = \frac{c_{p,\text{mix},i,sp}}{c_{p,\text{mix},i,sp} - \dfrac{\overline{R}}{\text{MW}_{\text{mix},sp}}} = \frac{0.2400\dfrac{\text{Btu}}{\text{lbm}\cdot{}^\circ\text{R}}}{0.2400\dfrac{\text{Btu}}{\text{lbm}\cdot{}^\circ\text{R}} - \dfrac{1,545.3488\dfrac{\text{ft}\cdot\text{lbf}}{\text{lbmol}\cdot{}^\circ\text{R}}\cdot\dfrac{\text{Btu}}{778.169\ \text{ft}\cdot\text{lbf}}}{28.945\dfrac{\text{lbm}}{\text{lbmol}}}} = 1.400$$

B-6.1.8 Total Temperature. See Nonmandatory Appendix C for an example of calculating total pressures and total temperatures in a piped inlet to a blower.

B-6.1.9 Isentropic Head and Isentropic Power at Specified Condition.

(a) Isentropic Head

$$W_s\left(\kappa_{\text{mix}},\ \text{MW}_{\text{mix}},\ T_i,\ r_p\right) = \frac{\kappa_{\text{mix}}}{\kappa_{\text{mix}} - 1}\cdot\frac{\overline{R}}{\text{MW}_{\text{mix}}}\cdot T_i\cdot\left(r_p^{\frac{\kappa_{\text{mix}}-1}{\kappa_{\text{mix}}}} - 1\right)$$

$$W_{s,sp} = W_s\left(\kappa_{\text{mix},sp},\ \text{MW}_{\text{mix},sp},\ T_{i,\text{tot},sp},\ r_{p,\text{tot},sp}\right) = \frac{\kappa_{\text{mix},sp}}{\kappa_{\text{mix},sp} - 1}\cdot\frac{\overline{R}}{\text{MW}_{\text{mix},sp}}\cdot T_{i,\text{tot},sp}\cdot\left(r_{p,tot,sp}^{\frac{\kappa_{\text{mix}.sp}-1}{\kappa_{\text{mix},sp}}} - 1\right)$$

$$= \frac{1.400}{1.400 - 1}\cdot\frac{1,545.3488\dfrac{\text{ft}\cdot\text{lbf}}{\text{lbmol}\cdot{}^\circ\text{R}}}{28.945\dfrac{\text{lbm}}{\text{lbmol}}}\cdot(40 + 459.67)^\circ\text{R}\cdot\left(1.738^{\frac{1,400-1}{1,400}} - 1\right) = 15,973\frac{\text{ft}\cdot\text{lbf}}{\text{lbm}}$$

In more useful units:

$$15,973\frac{\text{ft}\cdot\text{lbf}}{\text{lbm}}\cdot\frac{1\cdot\text{kW}}{44253.7\dfrac{\text{ft}\cdot\text{lbf}}{\text{min}}} = 0.3610\cdot\frac{\text{kW}}{\dfrac{\text{lbm}}{\text{min}}}$$

(b) Isentropic Power at Specified Condition

$$P_{s,sp} = q_{m,sp}\cdot W_{s,sp} = 747.1\frac{\text{lbm}}{\text{min}}\cdot 0.3610\frac{\text{kW}}{\dfrac{\text{lbm}}{\text{min}}} = 269.7\,\text{kW}$$

B-6.1.10 Isentropic Head at Test Condition.

(a) To back calculate the discharge pressure required to match isentropic head from the specified condition with the test condition, begin by calculating the relevant air mix properties for the gas at the test condition using the molecular weight of the air mix at test condition.

$$\text{MW}_{da} = 28.970\frac{\text{lbm}}{\text{lbmol}}$$

$$\text{MW}_{vp} = 18.015\frac{\text{lbm}}{\text{lbmol}}$$

x_{vp} = mole fraction of water vapor in mix = vapor pressure/total pressure

$$x_{vp}(T[{}^\circ\text{R}],\ \text{RH},\ p) = \frac{p_{sv}(T[{}^\circ\text{R}])\cdot\text{RH}}{p} = \frac{p_{vp}(T[{}^\circ\text{R}],\text{RH})}{p}$$

$$\text{MW}_{\text{mix}}\ (T[{}^\circ\text{R}],\ \text{RH},\ p) = \text{MW}_{vp}\cdot x_{vp}\ (T[{}^\circ\text{R}],\ \text{RH},\ p) + \text{MW}_{da}\cdot\left[1 - x_{vp}\ (T[{}^\circ\text{R}],\ \text{RH},\ p)\right]$$

For the test condition

$$\beta_{sv,sp} = \beta_{sv}(T_{i,t}[{}^\circ\text{R}]) = \frac{-7,202.2367}{524.77^\circ\text{R} - 70.431} = -15.9803$$

$$p_{sv,t} = p_{sv}(T_{i,t}[°R]) = 2.34908 \cdot 10^{6} \cdot e^{-15.9803} = 0.3066\frac{\text{lbf}}{\text{in.}^2}\text{abs}$$

$$p_{vp,t} = p_{vp}(T_{i,t}[°R], \text{RH}_t) = p_{sv}(T_{i,t}[°R]) \cdot \text{RH}_{\text{test}} = 0.3066\frac{\text{lbf}}{\text{in.}^2}\text{abs} \cdot 0.50 = 0.1533\frac{\text{lbf}}{\text{in.}^2}\text{abs}$$

$$x_{vp,t} = x_{vp}\left(T_{i,t}[°R], \text{RH}_t, p_{i,t}\right) = \frac{p_{vp,t}}{p_{i,t}} = \frac{0.1533\frac{\text{lbf}}{\text{in.}^2}\text{abs}}{14.150\frac{\text{lbf}}{\text{in.}^2}\text{abs}} = 0.0108$$

$$\text{MW}_{\text{mix},t} = \text{MW}_{\text{mix}}\left(T_{i,t}[°R], \text{RH}_t, p_{i,t}\right) = \text{MW}_{vp} \cdot x_{vp,t} + \text{MW}_{da}\left(1 - x_{vp,t}\right)$$

$$= 18.015\frac{\text{lbm}}{\text{lbmol}}0.0108 + 28.970\frac{\text{lbm}}{\text{lbmol}} \cdot (1 - 0.0108) = 28.851\frac{\text{lbm}}{\text{lbmol}}$$

(b) The test temperature ratio is an initial estimate based on isentropic temperature rise factored up for estimated efficiency.

$$r_t(r_{p,\text{tot},sp}, \kappa) = \frac{r_{p,\text{tot},sp}^{\frac{\kappa-1}{\kappa}} - 1}{0.65} + 1$$

where

0.65 = an assumed efficiency of the blower. For this initial estimate, assume that the ratio of specific heats, κ, = 1.40.

To initially estimate the test discharge pressure, assume the pressure ratio is the same as the specified pressure ratio:

$$r_{(p,\text{tot},t)} = r_{(p,\text{tot},sp)} = 1.738$$

$$p_{(d,t,\text{est})} = p_{(i,t)} \cdot r_{(p,\text{tot},t)} = 24.593\frac{\text{lbf}}{\text{in.}^2}\text{abs}$$

For the test condition

$$r_{t,t,\text{est}} = r_t\left(r_{p,\text{tot},sp}, 1.40\right) = \frac{r_{p,\text{tot},sp}^{\left(\frac{1.4-1}{1.4}\right)} - 1}{0.65} + 1 = \frac{1.738^{\left(\frac{1.4-1}{1.4}\right)} - 1}{0.65} + 1 = 1.263$$

Initial estimate of minimum $T_{d,t,\text{est}}$

$$T_{d,\text{tot},t,\text{est}} = T_{i,\text{tot},t} \cdot r_{t,t,\text{est}} = (65.1 + 459.67)°R \cdot 1.263 = 662.8°R$$

$$662.8\,°R - 459.67°R = 203.1°F$$

(c) To determine the ratio of specific heats at test conditions, calculate the molar specific heat of air and vapor using empirical function of temperature. Calculate the specific heat of the air mix at inlet temperature.

$$\bar{c}_{p,da}(T[°R]) = \begin{bmatrix} 3.64746 - \frac{0.708954}{10^3} \cdot T[°R] + \frac{9.41274}{10^6} \cdot T[°R]^2 \\ -\frac{0.254338}{10^9} \cdot T[°R]^3 \end{bmatrix} \cdot \overline{R}$$

$$\bar{c}_{p,vp}(T[°R]) = \left[4.05380 - \frac{0.51711}{10^3} \cdot T[°R] + \frac{1.05975}{10^6} \cdot T[°R]^2 - \frac{0.292781}{10^9} \cdot T[°R]^3\right] \cdot \bar{R}$$

where $\bar{R} = 1.98588 \frac{\text{Btu}}{\text{lbmol} \cdot °\text{R}}$

$$\bar{c}_{p,da,i,t} = \bar{c}_{p,da}(T_{i,t}[°R]) = \bar{c}_{p,da}[(65.1 + 459.67)°R] = 6.947 \frac{\text{Btu}}{\text{lbmol} \cdot °\text{R}}$$

$$\bar{c}_{p,vp,i,t} = \bar{c}_{p,vp}(T_{i,t}[°R]) = \bar{c}_{p,vp}[(65.1 + 459.67)°R] = 8.008 \frac{\text{Btu}}{\text{lbmol} \cdot °\text{R}}$$

(d) The specific heat of the test condition air mixture at inlet temperature is determined with the equation

$$c_{p,\text{mix}}\left(T[°R], x_{vp}, \text{MW}_{\text{mix}}\right) = \frac{\left(1 - x_{vp}\right) \cdot \bar{c}_{p,da}(T[°R]) + x_{vp} \cdot \bar{c}_{p,vp}(T[°R])}{\text{MW}_{\text{mix}}}$$

$$c_{p,\text{mix},i,t} = c_{p,\text{mix}}\left(T_{i,t}, x_{vp,t}, \text{MW}_{\text{mix},t}\right) = \frac{\left(1 - x_{vp,t}\right) \cdot \bar{c}_{p,da,i,t} + x_{vp,t} \cdot \bar{c}_{p,vp,i,t}}{\text{MW}_{\text{mix},t}}$$

$$= \frac{(1 - 0.0108) \cdot 6.947 \frac{\text{Btu}}{\text{lbmol} \cdot °\text{R}} + 0.0108 \cdot 8.008 \frac{\text{Btu}}{\text{lbmol} \cdot °\text{R}}}{28.851 \frac{\text{lbm}}{\text{lbmol}}} = 0.2412 \frac{\text{Btu}}{\text{lbm} \cdot °\text{R}}$$

(e) The ratio of specific heats at test conditions is determined by the equation

$$\kappa_{\text{mix},t} = \frac{c_{p,\text{mix},t}}{c_{p,\text{mix},t} - \frac{\bar{R}}{\text{MW}_{\text{mix},t}}} = \frac{0.2412 \frac{\text{Btu}}{\text{lbm} \cdot °\text{R}}}{0.2412 \frac{\text{Btu}}{\text{lbm} \cdot °\text{R}} - \frac{1,545.3488 \frac{\text{ft} \cdot \text{lbf}}{\text{lbmol} \cdot °\text{R}} \cdot \frac{\text{Btu}}{778.169\ \text{ft} \cdot \text{lbf}}}{28.851 \frac{\text{lbm}}{\text{lbmol}}}} = 1.399$$

(f) Solve the isentropic head equation to find the target discharge pressure that matches specified isentropic head at test conditions.

$$p_{d,\text{target},t}\left(W_{s,\text{target},t}, \text{MW}_{\text{mix}}, T_i, p_i, \kappa_{\text{mix}}\right) = \left(\frac{W_{s,\text{target},t}}{\frac{\kappa_{\text{mix}}}{\kappa_{\text{mix}} - 1} \cdot \frac{\bar{R}}{\text{MW}_{\text{mix}}} \cdot T_i} + 1\right)^{\frac{\kappa_{\text{mix}}}{\kappa_{\text{mix}} - 1}} \cdot p_{i,t}$$

$$p_{d,\text{target},t} = p_{d,\text{target},t}\left(W_{s,sp}, \text{MW}_{\text{mix},t}, T_{i,\text{tot},t}, p_{i,t}, \kappa_{\text{mix},t}\right)$$

$$= \left(\frac{1,5973 \frac{\text{ft} \cdot \text{lbf}}{\text{lb}}}{\frac{1.399}{1.399 - 1} \cdot \frac{1,545.3488 \frac{\text{ft} \cdot \text{lbf}}{\text{lbmol} \cdot °\text{RR}}}{28.851 \frac{\text{lbm}}{\text{lbmol}}} \cdot (65.1 + 459.67)\ °\text{R}} + 1\right)^{\frac{1.399}{1.399 - 1}} \cdot 14.150 \frac{\text{lbf}}{\text{in.}^2}\text{abs} = 24.0 \frac{\text{lbf}}{\text{in.}^2}\text{abs}$$

(g) Correct total pressure to static pressure using estimated velocity and density in test measurement duct.

$$D_{d,t} = 18\ \text{in.} = 1.5\ \text{ft}$$

$$A_{d,t} = \left(\frac{D_{d,t}}{2}\right)^2 \cdot \pi = \left(\frac{1.5\text{ ft}}{2}\right)^2 \cdot \pi = 1.77\text{ ft}^2$$

$$\rho_{d,\text{static},t} = \rho\left(T_{d,t}, \text{MW}_{\text{mix},t}, p_{d,t}\right) = \frac{p_{d,\text{target},t}}{\frac{\overline{R}}{\text{MW}_{\text{mix},t}} \cdot T_{d,t,\text{est}}} = \frac{24.0\frac{\text{lbf}}{\text{in.}^2}\text{abs} \cdot \frac{144\text{ in.}^2}{\text{ft}^2}}{\frac{1,545.3488\frac{\text{ft}\cdot\text{lbf}}{\text{lbmol}\cdot{}^\circ\text{R}}}{28.851\frac{\text{lbm}}{\text{lbmol}}} \cdot 662.8\,^\circ\text{R}} = 0.0973\frac{\text{lbm}}{\text{ft}^3}$$

$$V_{d,t,\text{est}} = \frac{q_{sp} \cdot \frac{\rho_{i,sp}}{\rho_{d,\text{static},t}}}{A_{d,t}} = \frac{10522\,\frac{\text{ft}^3}{\text{min}} \cdot \frac{0.0710\frac{\text{lbm}}{\text{ft}^3}}{0.0973\frac{\text{lbm}}{\text{ft}^3}}}{1.77\text{ ft}^2} = 4,338\,\frac{\text{ft}}{\text{min}}$$

$$p_{d,\text{static,target},t} = p_{d,\text{target},t} - \frac{\rho_{d,\text{static},t} \cdot (V_{d,t})^2}{2g_c}$$

$$= 24.0\frac{\text{lbf}}{\text{in.}^2}\text{abs} - \frac{0.0973\frac{\text{lbm}}{\text{ft}^3} \cdot \left(4,338\frac{\text{ft}}{\text{min}} \cdot \frac{1\cdot\text{min}}{60\cdot\text{sec}}\right)^2 \cdot \frac{1\text{ ft}}{1\text{ ft}} \cdot \frac{1\text{ lbf}}{32.1741\frac{\text{ft}\cdot\text{lb}}{\text{sec}^2}} \cdot \frac{1\text{ ft}^2}{144\text{ in.}^2}}{2} = 23.9\frac{\text{lbf}}{\text{in.}^2}\text{abs}$$

$$p_{d,\text{static,target},t,ga} = p_{d,\text{static,target},t} - p_{a,t} = 23.9\frac{\text{lbf}}{\text{in.}^2}\text{abs} - 14.30\,\frac{\text{lbf}}{\text{in.}^2}\text{abs} = 9.60\frac{\text{lbf}}{\text{in.}^2}$$

B-7 STEP 6: RUN THE TEST

B-7.1 Operate the Blower

With target volumetric flow rate and pressure determined, the test is run with the following results:

$$q_{m,t} = 762.9\frac{\text{lbm}}{\text{min}}$$

$$p_{d,\text{static},t,ga} = 9.60\frac{\text{lbf}}{\text{in.}^2}$$

$$T_{d,t} = (208 + 459.67)^\circ\text{R}$$
$$P_t = 402\text{ kW}$$

Inlet condition is measured in room at zero velocity. Discharge condition is measured in an 18-in. diameter pipe.

$$D_{\text{impeller}} = 17.72\text{ in.} \quad N_t = 12637\,\frac{1}{\text{min}}$$

B-8 STEP 7: CALCULATE PERFORMANCE AND COMPARE PARAMETERS

B-8.1 Predict Thermodynamic Performance at Specified Conditions by Test Results

(a) Calculate vapor pressure, mole fractions, and molecular weight of inlet air at test conditions. Use values determined in para. B-6.1.10(a).

$$x_{vp,t} = 0.0108$$

$$\text{MW}_{\text{mix},t} = 28.851\frac{\text{lbm}}{\text{lbmol}}$$

(b) Determine actual specific heat of the test conditions air mixture at inlet temperature. Use values determined in para. B-6.1.10(d).

$$c_{p,\text{mix},i,t} = 0.2412 \frac{\text{Btu}}{\text{lbm} \cdot {}^\circ\text{R}}$$

(c) Determine actual ratio of specific heat at test conditions. Use values determined in Step 5, para. B-6.1.10(c).

$$\kappa_{\text{mix},t} = 1.399$$

B-8.2 Air Velocities

(a) Calculate velocities for inlet and discharge to find total pressure and temperatures.
$V_{i,t}$ = 0. The inlet condition is room air

$$D_{d,t} = 18 \text{ in.} = 1.5 \text{ ft}$$

$$A_{d,t} = \left(\frac{D_{d,t}}{2}\right)^2 \cdot \pi = \left(\frac{1.5 \text{ ft}}{2}\right)^2 \cdot \pi = 1.77 \text{ ft}^2$$

$$\rho_{d,\text{static},t} = \rho\left(T_{d,t}, \text{MW}_{\text{mix},t}, p_{d,t}\right) = \frac{(9.600 + 14.30)\dfrac{\text{lbf}}{\text{in.}^2}\text{abs} \cdot \dfrac{144 \text{ in.}^2}{\text{ft}^2}}{\dfrac{1,545.3488\dfrac{\text{ft} \cdot \text{lbf}}{\text{lbmol} \cdot {}^\circ\text{R}}}{28.851\dfrac{\text{lbm}}{\text{lbmol}}} \cdot (208 + 459.67)\ {}^\circ\text{R}} = 0.0962$$

$$V_{d,t} = \frac{q_{m.t}}{\rho_{\text{static},t} \cdot A_{d,t}} = \frac{762.9\dfrac{\text{lbm}}{\text{min}}}{0.0962\dfrac{\text{lbm}}{\text{ft}^3} \cdot 1.77 \text{ ft}^2} = 4{,}480\frac{\text{ft}}{\text{min}}$$

(b) Calculate total pressures. The inlet condition is room air; velocity is zero.

$$p_{i,t} = 14.150\frac{\text{lbf}}{\text{in.}^2}\text{abs}$$

$$p_{d,t} = p_{d,\text{static},t} + \frac{\rho_{d,\text{static},t} \cdot (V_{d,t})^2}{2g_c} = (9.600 + 14.300) + \frac{0.0962\dfrac{\text{lbm}}{\text{ft}^3} \cdot \left(4{,}480\dfrac{\text{ft}}{\text{min}} \cdot \dfrac{1 \text{ min}}{60 \text{ sec}}\right)^2 \cdot \dfrac{1 \text{ ft}^2}{144 \text{ in.}^2}}{2 \cdot 32.1741\dfrac{\text{ft} \cdot \text{lbm}}{\text{lbf} \cdot \text{sec}^2}} = 23.958\frac{\text{lbf}}{\text{in.}^2}$$

(c) Calculate total temperatures (specific heats required). The inlet condition is measured in room at zero velocity.

$$T_{i,\text{tot},t} = T_{i,t} = (65.1 + 459.67)^\circ\text{R}$$

Recovery factor for air for thermocouples, r_f = 0.65.
(1) Specific heat for inlet air temp, for practical purposes, is sufficient for estimating total T at discharge.

$$T_{d,\text{tot},t} = T_{d,t} + \left(1 - r_f\right) \cdot \frac{{V_{d,t}}^2}{2 \cdot J \cdot g_c \cdot c_{p,i,t}}$$

$$= (208 + 459.67)^\circ\text{R} + (1 - 0.65) \cdot \frac{\left(4{,}480\dfrac{\text{ft}}{\text{min}} \cdot \dfrac{1 \text{ min}}{60 \text{ sec}}\right)^2}{2 \cdot 778.169\dfrac{\text{ft} \cdot \text{lbf}}{\text{Btu}} \cdot 32.1741\dfrac{\text{ft} \cdot \text{lbm}}{\text{lbf} \cdot \text{sec}^2}} = 667.83^\circ\text{R} = 208.16^\circ\text{F}$$

B-8.3 Total Densities

Calculate total densities for test conditions.

$$\rho(T[°\text{F}],\ T,\ \text{RH},\ p) = \frac{p}{\dfrac{\overline{R}}{\text{MW}_{\text{mix}}\,(T[°\text{R}],\text{RH},p)} \cdot T}$$

$$\rho_{i,t} = \rho_{i,\text{static},t} = \rho\left(T_{i,t}[°\text{R}],\ T_{i,t},\ \text{RH}_t,\ p_{i,t}\right) = \frac{14.150\dfrac{\text{lbf}}{\text{in.}^2}\text{abs} \cdot \dfrac{144\ \text{in.}^2}{\text{ft}^2}}{\dfrac{1,545.3488\dfrac{\text{ft} \cdot \text{lbf}}{\text{lbmol} \cdot °\text{R}}}{28.851\dfrac{\text{lbm}}{\text{lbmol}}} \cdot (65.1 + 459.67)\ °\text{R}} = 0.0725\frac{\text{lbm}}{\text{ft}^3}$$

$$\rho_{d,t} = \frac{p_{d,t}}{\dfrac{\overline{R}}{\text{MW}_{\text{mix},t}} \cdot T_{d,t}} = \frac{23.958\ \dfrac{\text{lbf}}{\text{in.}^2}\text{abs} \cdot \dfrac{144\ \text{in.}^2}{\text{ft}^2}}{\dfrac{1,545.3488\dfrac{\text{ft} \cdot \text{lbf}}{\text{lbmol} \cdot °\text{R}}}{28.851\dfrac{\text{lb}}{\text{lbmol}}} \cdot 667.83\ °\text{R}} = 0.0964\frac{\text{lbm}}{\text{ft}^3}$$

B-8.4 Inlet Volumetric Flow Rate at Test Conditions

Calculate the volumetric flow rate from the test.

$$q_{v,t} = \frac{q_{m.t}}{\rho_t} = \frac{762.9\dfrac{\text{lbm}}{\text{min}}}{0.0725\dfrac{\text{lbm}}{\text{ft}^3}} = 10{,}523\frac{\text{ft}^3}{\text{min}}$$

B-8.5 Isentropic Head at Test Conditions

Use actual isentropic head and power from the test.

(a) Isentropic Head

$$W_s\left(\kappa_{\text{mix}},\ \text{MW}_{\text{mix}},\ T_i,\ r_{p,\text{tot},sp}\right) = \frac{\kappa_{\text{mix}}}{\kappa_{\text{mix}} - 1} \cdot \frac{\overline{R}}{\text{MW}_{\text{mix}}} \cdot T_i \cdot \left(r_{p,\text{tot},sp}^{\ \frac{\kappa_{\text{mix}}-1}{\kappa_{\text{mix}}}} - 1\right)$$

$$r_{p,\text{tot},t} = \frac{p_{d,t}}{p_{i,t}} = \frac{23.958\ \dfrac{\text{lbf}}{\text{in.}^2}\text{abs}}{14.150\dfrac{\text{lbf}}{\text{in.}^2}\text{abs}} = 1.693$$

$$W_{s,t} = W_s\left(\kappa_{\text{mix},t},\ \text{MW}_{\text{mix},t},\ T_{i,t},\ r_{p,\text{tot},t}\right) = \frac{\kappa_{\text{mix},t}}{\kappa_{\text{mix},t} - 1} \cdot \frac{\overline{R}}{\text{MW}_{\text{mix},t}} \cdot T_{i,t} \cdot \left(r_{p,\text{tot},t}^{\left(\frac{\kappa_{\text{mix}.t}-1}{\kappa_{\text{mix},t}}\right)} - 1\right)$$

$$= \frac{1.399}{1.399 - 1} \cdot \frac{1{,}545.3488\dfrac{\text{ft} \cdot \text{lbf}}{\text{lbmol} \cdot °\text{R}}}{28.851\dfrac{\text{lbm}}{\text{lbmol}}} \cdot (65.1 + 459.67)°\text{R} \cdot \left(1.693^{\left(\frac{1.399-1}{1.399}\right)} - 1\right) = 16{,}159\ \text{ft} \cdot \text{lbf/lbm}$$

In more useful units:

$$16{,}159\frac{\text{ft} \cdot \text{lbf}}{\text{lbm}} \cdot \frac{1 \cdot \text{kW}}{44{,}253.7\dfrac{\text{ft} \cdot \text{lbf}}{\text{min}}} = 0.3651\frac{\text{kW}}{\dfrac{\text{lbm}}{\text{min}}}$$

(b) Isentropic Power at Test Condition

$$P_{s,t} = q_{m,t} \cdot W_{s,t} = 762.9\frac{\text{lbm}}{\text{min}} \cdot 0.3651\frac{\text{kW}}{\dfrac{\text{lbm}}{\text{min}}} = 278.5\ \text{kW}$$

B-9 PERMISSIBLE DEVIATIONS

(a) Check for permissible deviations between test and specified operating conditions similitude parameters per para. 3-5.4.

(1) Check specific volume ratio, r_v.

Specific volume: $v = \frac{1}{\rho}$ $r_v = \frac{v_i}{v_d} = \frac{\rho_d}{\rho_i}$

(-a) Finding $r_{v,sp}$ requires an estimate of the discharge temperature, T_d, at the specified condition, which can be estimated based on the discharge temperature from the test condition.

$$T_{d,sp,pr} = T_{i,sp} \cdot \left[\frac{\left[\left(\frac{p_{d,sp}}{p_{i,sp}} \right)^{\frac{\kappa_{mix,sp}-1}{\kappa_{mix,sp}}} - 1 \right] \cdot \left[\frac{T_{d,t}}{T_{i,t}} - 1 \right]}{\left(\frac{p_{d,t}}{p_{i,t}} \right)^{\frac{\kappa_{mix,t}-1}{\kappa_{mix,t}}} - 1} \right] + 1$$

$$T_{d,sp,pr} = (40 + 459.67)°\text{R} \cdot \left[\frac{\left[\left(\frac{22.850 \frac{\text{lbf}}{\text{in.}^2}\text{abs}}{13.150 \frac{\text{lbf}}{\text{in.}^2}\text{abs}} \right)^{\frac{1.400-1}{1.400}} - 1 \right] \cdot \left[\frac{667.83°\text{R}}{524.77°\text{R}} - 1 \right]}{\left(\frac{23.960 \frac{\text{lbf}}{\text{in.}^2}\text{abs}}{14.150 \frac{\text{lbf}}{\text{in.}^2}\text{abs}} \right)^{\frac{1.399-1}{1.399}} - 1} \right] + 1 = 643.39°\text{R}$$

(-b) Once the discharge temperature at the specified condition is estimated, estimate the discharge density at the specified condition.

$$\rho_{d,sp,pr} = \frac{p_{d,sp}}{\frac{\bar{R}}{MW_{mix,sp}} \cdot T_{d,sp,pr}} = \frac{22.850 \frac{\text{lbf}}{\text{in.}^2}\text{abs} \cdot \frac{144 \text{ in.}^2}{\text{ft}^2}}{\frac{1{,}545.3488 \frac{\text{ft} \cdot \text{lbf}}{\text{lbmol} \cdot °\text{R}}}{28.945 \frac{\text{lbm}}{\text{lbmol}}} \cdot 643.39\ °\text{R}} = 0.0958 \frac{\text{lbm}}{\text{ft}^3}$$

Specific volume ratio at specified conditions

$$r_{v,sp} = \frac{\rho_{d,sp,pr}}{\rho_{i,sp}} = \frac{0.0958 \frac{\text{lbm}}{\text{ft}^3}}{0.0710 \frac{\text{lbm}}{\text{ft}^3}} = 1.349$$

Specific volume ratio at test condition

$$r_{v,t} = \frac{\rho_{d,t}}{\rho_{i,t}} = \frac{0.0964 \frac{\text{lbm}}{\text{ft}^3}}{0.0725 \frac{\text{lbm}}{\text{ft}^3}} = 1.330$$

Specific volume ratio at test condition as percent of specific volume ratio at specified condition:

$$\frac{r_{v,t}}{r_{v,sp}} \cdot 100\% = \frac{1.330}{1.349} \cdot 100\% = 98.6\%$$

This conforms to the range limit of 95% to 105% established in Table 3-5.4-1.

(2) Check inlet volumetric flow rate, q_v.

$$q_{v,sp} = 10{,}522\ \frac{\text{ft}^3}{\text{min}} \qquad q_{v,t} = 10{,}523\ \frac{\text{ft}^3}{\text{min}}$$

Inlet volumetric flow rate at test conditions as percent of inlet volumetric flow rate at specified conditions:

$$\frac{q_{v,t}}{q_{v,sp}} \cdot 100\% = \frac{10{,}523\ \frac{\text{ft}^3}{\text{min}}}{10{,}522\ \frac{\text{ft}^3}{\text{min}}} \cdot 100\% = 100.01\%$$

This conforms to the range limit of 99% to 101% established in Table 3-5.4-1.

(3) Check isentropic head, W_s.

$$W_{s,sp} = 0.3610\ \frac{\text{kW}}{\frac{\text{lbm}}{\text{min}}} \qquad W_{s,t} = 0.3651\ \frac{\text{kW}}{\frac{\text{lbm}}{\text{min}}}$$

$$\frac{W_{s,t}}{W_{s,sp}} \cdot 100\% = \frac{0.3651\ \frac{\text{kW}}{\frac{\text{lbm}}{\text{min}}}}{0.3610\ \frac{\text{kW}}{\frac{\text{lbm}}{\text{min}}}} \cdot 100\% = 101\%$$

This conforms to the range limit of 100% to 101% established in Table 3-5.4-1.

(4) Check machine Mach number, M_m.

$$M_m = \frac{U_2}{\sqrt{\kappa_{\text{mix}} \cdot \frac{\overline{R}}{MW_{\text{mix}}} \cdot g_c \cdot T_i}}$$

For this test, inlet volumetric flow rate was matched; therefore, impeller speed and impeller diameter from test are assumed to be same as at specified conditions. $N_{sp} = N_t = 12{,}637$ rpm.

$$M_{m,sp} = \frac{N_{sp} \cdot D_2 \cdot \pi}{\sqrt{\kappa_{\text{mix},sp} \cdot \frac{\overline{R}}{MW_{\text{mix},sp}} \cdot g_c \cdot T_{i,sp}}} = \frac{12{,}637\ \frac{1}{\text{min}} \cdot \frac{1\text{min}}{60\text{sec}} \cdot \frac{17.72\ \text{in.} \cdot \frac{1\ \text{ft}}{12\ \text{in.}}}{2} \cdot 2 \cdot \pi}{\sqrt{1.400 \cdot \frac{1{,}545.3488 \frac{\text{ft} \cdot \text{lbf}}{\text{lbmol} \cdot {}^\circ\text{R}}}{28.945 \frac{\text{lbm}}{\text{lbmol}}} \cdot 32.1741 \cdot \frac{\frac{\text{ft} \cdot \text{lb}}{\text{sec}^2}}{\text{lbf}} \cdot 499.67\ {}^\circ\text{R}}} = 0.8913$$

$$M_{m,t} = \frac{N_t \cdot D_2 \cdot \pi}{\sqrt{\kappa_{\text{mix},t} \cdot \frac{\overline{R}}{\text{MW}_{\text{mix},t}} \cdot g_c \cdot T_{i,t}}} = \frac{12{,}637\ \frac{1}{\text{min}} \cdot \frac{1\text{min}}{60\text{sec}} \cdot \frac{17.72\ \text{in.} \cdot \frac{1\ \text{ft}}{12\ \text{in.}}}{2} \cdot 2 \cdot \pi}{\sqrt{1.399 \cdot \frac{1{,}545.3488 \frac{\text{ft} \cdot \text{lbf}}{\text{lbmol} \cdot {}^\circ\text{R}}}{28.851 \frac{\text{lbm}}{\text{lbmol}}} \cdot 32.1741 \cdot \frac{\frac{\text{ft} \cdot \text{lbm}}{\text{sec}^2}}{\text{lbf}} \cdot 524.77\ {}^\circ\text{R}}} = 0.8635$$

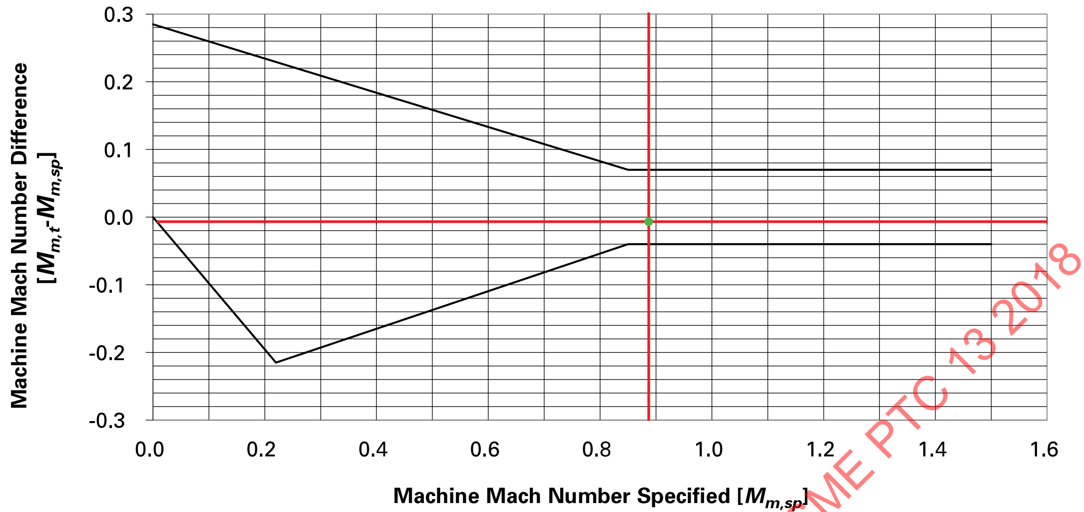
A check of the machine Mach numbers achieved in this example against Figure B-9-1 demonstrates that the result conforms to these graphic limits.

$$M_{m,t} - M_{m,sp} = 0.8635 - 0.8913 = -0.0278$$

(5) All deviations of similitude parameters between test and specified operating conditions are within permissible ranges.

(b) Calculate the discharge pressure predicted for the specified condition based on the test result.

Figure B-9-1 Allowable Machine Mach Numbers for Dynamic Blowers



$$p_{d,\text{target}}\left(W_{s,\text{target}},\ \text{MW}_{\text{mix}},\ T_i,\ p_i,\ \kappa_{\text{mix}}\right) = \left(\frac{W_{s,\text{target}}}{\frac{\kappa_{\text{mix}}}{\kappa_{\text{mix}}-1}\cdot\frac{\overline{R}}{\text{MW}_{\text{mix}}}\cdot T_i} + 1\right)^{\frac{\kappa_{\text{mix}}}{\kappa_{\text{mix}}-1}}\cdot p_i$$

$$p_{d,pr} = p_{d,\text{target}}\left(W_{s,t},\ \text{MW}_{\text{mix},sp},\ T_{i,sp},\ p_{i,sp,\text{adj}},\ \kappa_{\text{mix},sp}\right)$$

$$= \left(\frac{16{,}159\frac{\text{ft}\cdot\text{lbf}}{\text{lbm}}}{\frac{1.400}{1.400-1}\cdot\frac{1{,}545.3488\frac{\text{ft}\cdot\text{lbf}}{\text{lbmol}\cdot{}^\circ\text{R}}}{28.945\frac{\text{lbm}}{\text{lbmol}}}\cdot(40+459.67)\,{}^\circ\text{R}} + 1\right)^{\frac{1.400}{1.400-1}}\cdot 13.15\frac{\text{lbf}}{\text{in.}^2}\text{abs} = 22.99\frac{\text{lbf}}{\text{in.}^2}\text{abs}$$

$$p_{d,pr,ga} = p_{d,pr} - p_{a,t} = 22.93\frac{\text{lbf}}{\text{in.}^2}\text{abs} - 13.95\frac{\text{lbf}}{\text{in.}^2}\text{abs} = 8.98\frac{\text{lbf}}{\text{in.}^2}$$

B-10 STEP 8: RUN FINAL CALCULATIONS

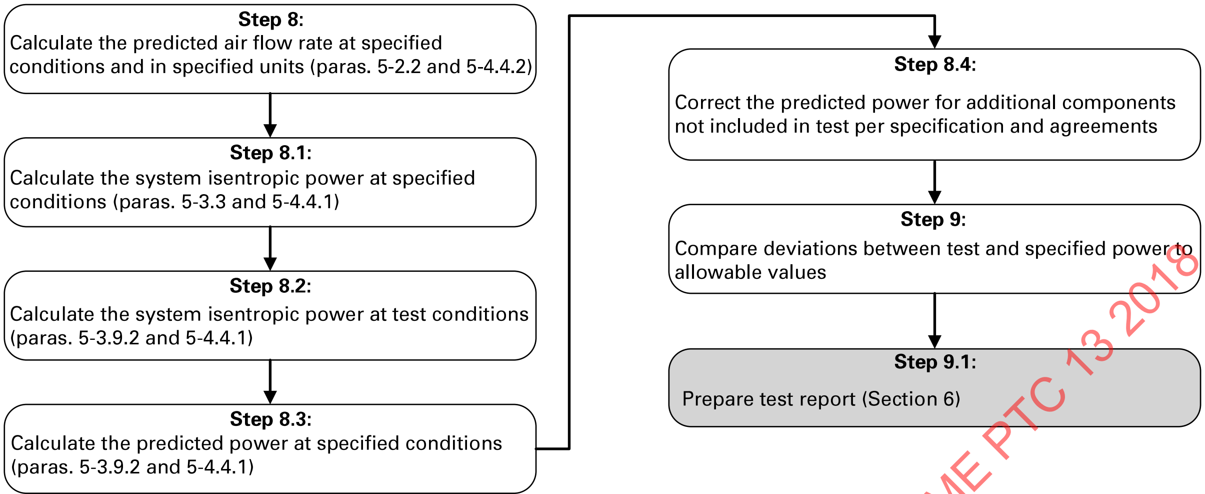
As indicated in Figure B-10-1, the next steps in the procedure include completing the calculations and comparing deviations between test and specified conditions.

B-10.1 Predict Standard Conditions

Predict standard-condition volumetric flow rate at specified conditions, using the flow measurement obtained from the test condition.

$$q_{v,\text{std}}\left(q_{v,sp},\ T_{\text{std}},\ T_{sp},\ T_{\text{std}}[{}^\circ\text{R}],\ T_{sp}[{}^\circ\text{R}],\ p_{\text{std}},\ p_{sp},\ \text{RH}_{\text{std}},\ \text{RH}_{sp}\right) = q_{v,t}\cdot\left[\frac{p_{sp}-p_{vp}\left(T_{sp}[{}^\circ\text{R}],\text{RH}_{sp}\right)}{p_{\text{std}}-p_{vp}\left(T_{\text{std}}[{}^\circ\text{R}],\text{RH}_{\text{std}}\right)}\right]\cdot\left(\frac{T_{\text{std}}}{T_{sp}}\right)$$

Figure B-10-1 Final Calculations



$$q_{v,pr,std} = q_{v,std}\left(q_{v,t},\, T_{std},\, T_{i,sp},\, T_{std}[°F],\, T_{i,sp}[°F], p_{std},\, p_{i,sp,adj},\, RH_{std},\, RH_{sp}\right) = q_{v,t}\cdot\left(\frac{p_{i,sp,adj}-p_{vp,sp}}{p_{i,std}-p_{vp,std}}\right)\cdot\left(\frac{T_{i,std}}{T_{sp}}\right)$$

$$= 10{,}523\frac{\text{ft}^3}{\text{min}}\cdot\left(\frac{(13.150-0.0303)\dfrac{\text{lbf}}{\text{in.}^2}\text{abs}}{(14.700-0.1220)\dfrac{\text{lbf}}{\text{in.}^2}\text{abs}}\right)\cdot\left(\frac{(68+459.67)\ °\text{R}}{(40+459.67)\ °\text{R}}\right) = 10{,}001\frac{\text{ft}^3}{\text{min}}$$

B-10.2 Predict Power

Power shall be predicted for the specified condition based on the test result. Adjust the measured power at test by the ratio of isentropic power at specified conditions to isentropic power at test conditions. Use the isentropic power at specified condition determined in Step 5, para. B-6.1.10.

$$P_{s,sp} = q_{m,sp}\cdot W_{s,sp} = 747.1\frac{\text{lbm}}{\text{min}}\cdot 0.3610\frac{\text{kW}}{\dfrac{\text{lbm}}{\text{min}}} = 269.7\ \text{kW}$$

Use the isentropic power at test condition from Step 7, para. B-8.5(b).

$$P_{s,t} = q_{m,t}\cdot W_{s,t} = 762.9\frac{\text{lbm}}{\text{min}}\cdot 0.3651\frac{\text{kW}}{\dfrac{\text{lbm}}{\text{min}}} = 278.5\ \text{kW}$$

Predicted power at specified condition is from power measured at test condition.

$$P_{pr} = P_t\cdot\frac{P_{s,sp}}{P_{s,t}} = 402\ \text{kW}\cdot\frac{269.7\ \text{kW}}{278.5\ \text{kW}} = 389\ \text{kW}$$

This example does not include corrections for additional components not included in the test. See Nonmandatory Appendix C for examples of these types of corrections.

B-11 STEP 9: PERFORMANCE DEVIATION REPORTING AND TEST REPORTING

See Nonmandatory Appendix C.

Nonmandatory Appendix C
Sample Calculation: PD Blowers

C-1 OBJECT AND SCOPE

This Appendix presents an example of the calculation procedure intended for positive displacement (PD) blowers. This sample procedure illustrates a screw-type PD machine with variable-speed operation, an external inlet filter, and no external cooling devices. These calculations shall demonstrate a test configuration that is not identical to the specified configuration.

C-1.1 Reference Equations

The physical constants and important properties used for reference in this Appendix are listed in Table C-1.1-1.

In addition, the formulas that follow shall be used to calculate the percentage variance and deviation between specified and measured parameters. Compare the results to Table 3-5.4-2.

(a)

$$\text{percentage error} = \frac{\text{measured value} - \text{specified value}}{\text{specified value}} \cdot 100$$

(b)

$$\text{deviation} = \frac{\text{measured value}}{\text{specified value}} \cdot 100$$

C-2 STEP 1: DETERMINE CONDITIONS AND PERFORMANCE

The first step, as illustrated in Figure C-2-1, shall be to determine the specified standard conditions and the corresponding thermodynamic properties.

C-2.1 Determine Specified Conditions

Determine the specified conditions for mass flow rate for use in conversion to volumetric flow rate. For this example, flow shall be defined by SCFM conditions of 68°F, 14.7 psia, and 36% relative humidity. Specified temperature and pressure shall be assumed to be static and shall not include velocity-head effects unless otherwise indicated. The properties of air at the specified standard conditions are shown in Table C-2.1-1.

C-2.2 Determine Specified Performance

The specified ambient, inlet, and discharge conditions for performance point(s) shall be determined. For specified design points of the PD blower used in this Appendix, refer to Table C-2.2-1.

The specifications of the test installation identify inlet piping losses of 0.15 psi as a result of field piping between ambient air and the inlet flange connection. The specified isolation transformer is not included in the test equipment. The owner and the supplier agree that an allowance of 2% of measured power shall be included in electric power measurements to allow for transformer losses.

The test specification requires the isentropic wire-to-air system efficiency and the SCFM/kW at the design point be included in the reported data.

Table C-1.1-1 Physical Constants and Properties

Physical Constant/Property, Symbol	Value
Universal gas constant, $\bar{R}$	$\bar{R} = 1{,}545.3488 \frac{\text{ft} \cdot \text{lbf}}{\text{lbmol} \cdot {}^\circ\text{R}} = 1.98588 \frac{\text{Btu}}{\text{lbmol} \cdot {}^\circ\text{R}}$
Molecular weight of dry air, MW_{da}	$MW_{da} = 28.97 \frac{\text{lbm}}{\text{lbmol}}$
Molecular weight of water vapor, MW_{vp}	$MW_{vp} = 18.015 \frac{\text{lbm}}{\text{lbmol}}$
Power equivalence, P	1 hp = 0.7457 kW $1 \frac{\text{Btu}}{\text{hr}} = 2.9307 \cdot 10^{-4}$ kW
Dimensional constant, g_c	$g_c = 32.1741 \frac{\text{lbm} \cdot \text{ft}}{\text{lbf} \cdot \text{sec}^2}$
Temperature equivalence, T	°R = °F + 459.67
Pressure equivalence, p	psia = psig + p_a = psig + 14.7 at standard conditions

Figure C-2-1 Preliminary Steps

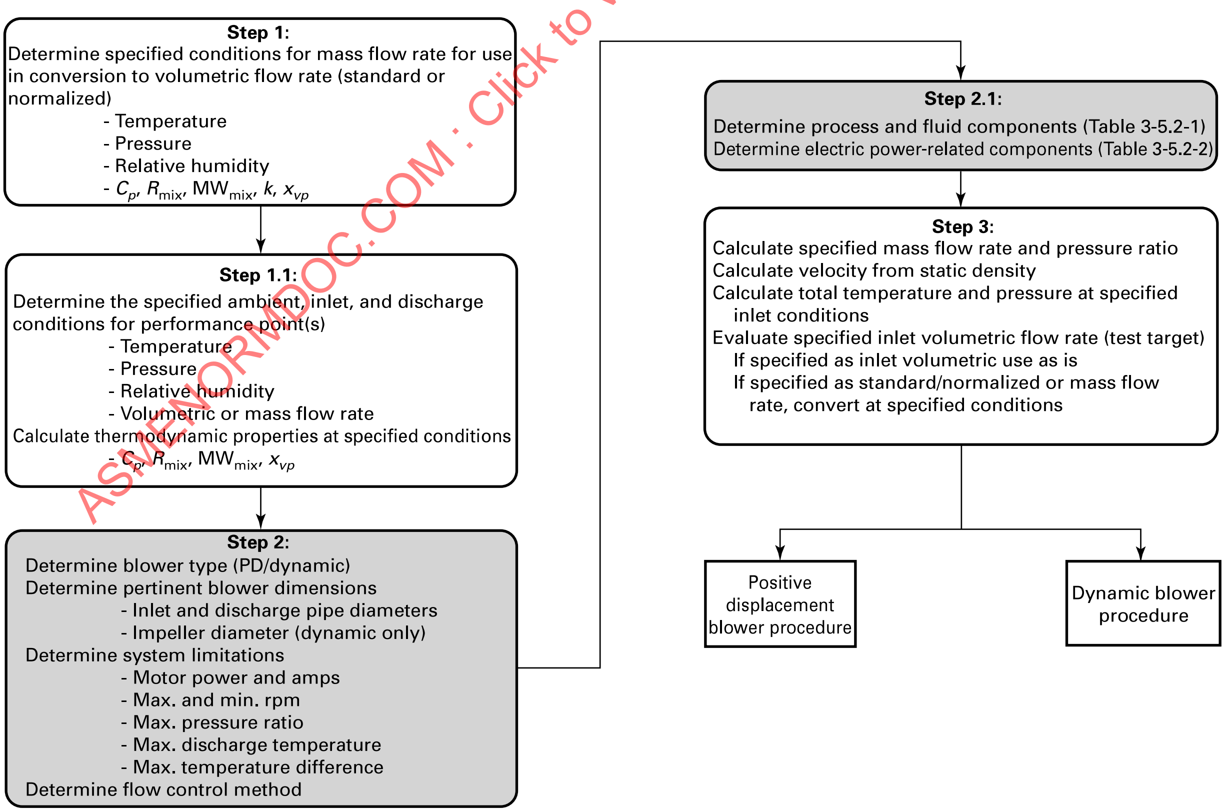


Table C-2.1-1 Properties of Air at Specified Conditions

Parameter, Symbol (Standard Condition)	Value
Saturated vapor pressure, $p_{sv,\mathrm{std}}$	0.339 psia
Water vapor pressure, $p_{vp,\mathrm{std}}$	0.122 psia
Mole fraction proportions of dry air/water vapor, $x_{vp,\mathrm{std}}$	$8.30 \cdot 10^{-3}$
Mole weight of mixture of dry air/water vapor, $\mathrm{MW}_{\mathrm{mix,std}}$	$28.88 \frac{\mathrm{lbm}}{\mathrm{lbmol}}$
Standard mixture gas constant, $R_{\mathrm{mix,std}}$	$53.51 \frac{\mathrm{ft} \cdot \mathrm{lbf}}{\mathrm{lbm} \cdot {}^{\circ}\mathrm{R}} = 0.0688 \frac{\mathrm{Btu}}{\mathrm{lbm} \cdot {}^{\circ}\mathrm{R}}$ [Note (1)]
Air density of mixture, $\rho_{\mathrm{mix,std}}$	$0.075 \frac{\mathrm{lbm}}{\mathrm{ft}^3}$
Specific heat of dry air, $c_{p,da,\mathrm{std}}$	$0.240 \frac{\mathrm{Btu}}{\mathrm{lbm} \cdot {}^{\circ}\mathrm{R}}$
Specific heat of water vapor, $c_{p,\mathrm{vap,std}}$	$0.445 \frac{\mathrm{Btu}}{\mathrm{lbm} \cdot {}^{\circ}\mathrm{R}}$
Specific heat of mixture, $c_{p,\mathrm{mix,std}}$	$0.241 \frac{\mathrm{Btu}}{\mathrm{lbm} \cdot {}^{\circ}\mathrm{R}}$
Ratio of mixture specific heats, $\kappa_{\mathrm{mix,std}}$	1.400

GENERAL NOTE: These values are based on the empirical equations of subsection 5-2.

NOTE: (1) $1 \frac{\mathrm{Btu}}{\mathrm{lbm} \cdot {}^{\circ}\mathrm{R}} = 778.17 \frac{\mathrm{ft} \cdot \mathrm{lbf}}{\mathrm{lbm} \cdot {}^{\circ}\mathrm{R}}$

Table C-2.2-1 Specified Design Points

Parameter	Specified Value
Ambient conditions at design flow	13.95 psia barometric pressure, 100°F, 90% RH
Electric power	480 VAC, 3-phase, 60 Hz
Capacity	2,500 SCFM at discharge
Discharge pressure	8.50 psig at specified capacity
Power consumption	118 kW maximum
Site piping	Schedule 40, 14 in. inlet (13.124 in. inner diameter [ID]), 12 in. discharge (11.938 in. ID)

C-2.3 Run Calculations

Once specified conditions and performance have been determined, calculate the thermodynamic characteristics at the specified ambient conditions.

C-2.3.1 Inlet and Discharge Pressures and Temperatures. Calculate inlet and discharge pressures and temperatures at the specified design point. At ambient conditions, static and total pressures and temperatures are equal.

$$p_{a,sp} = 13.95 \text{ psia}$$

$$p_{i,sp,\mathrm{static}} = p_{a,sp} - \Delta p_i = 13.95 - 0.15 = 13.80 \text{ psia}$$

$$p_{d,sp,\mathrm{static}} = p_{a,sp} + p_{d,sp,ga} = 13.95 + 8.50 = 22.45 \text{ psia}$$

$$T_{a,sp} = 100 + 459.67 = 559.67^{\circ}\mathrm{R}$$

C-2.3.2 Moisture Content and Molecular Weight of Air. Determine the moisture content and molecular weight of air at the specified ambient conditions using the following empirical formulas:

$$\beta_{a,sp} = \frac{-7{,}202.2367}{°R - 70.431} = \frac{--7{,}202.2367}{559.67\ 70.431} = -14.7213$$

$$p_{sv,sp} = 2{,}349.081 \cdot 10^3 e^{\beta a,sp}$$

$$p_{sv,sp} = 2{,}349.081 \cdot 10^3 \cdot 2.71828^{-14.7213} = 0.9495 \text{ psia}$$

$$p_{vp,sp} = \text{RH} \cdot p_{sv,sp} = 0.9 \cdot 0.9495 = 0.8546 \text{ psia}$$

where

$x_{vp,sp}$ = lbmol water per lbmol dry air

$$x_{vp,sp} = \frac{p_{vp,a,sp}}{p_{a,sp}} = \frac{0.8546}{13.95} = 0.0613$$

Next, determine the molecular weight of the mixture of water vapor and air.

$$\text{MW}_{\text{mix},sp} = (1 - x_{v,a,sp}) \cdot \text{MW}_{da} + x_{vp,a,sp} \cdot \text{MW}_{vp}$$

$$\text{MW}_{\text{mix},sp} = (1 - 0.0613) \cdot 28.97 + 0.0613 \cdot 18.015$$

$$\text{MW}_{\text{mix},sp} = 28.30 \frac{\text{lbm}}{\text{lbmol}}$$

C-2.3.3 Specific Mixture Gas Constant. Calculate the specific mixture gas constant at the specified ambient conditions. Note that the molecular weight and gas constant of the air at specified conditions will be unchanged throughout the system.

$$R_{\text{mix},sp} = \frac{\overline{R}}{\text{MW}_{\text{mix},a,sp}} = \frac{1{,}545.35 \frac{\text{ft} \cdot \text{lbf}}{\text{lbmol} \cdot °\text{R}}}{28.30 \frac{\text{lbm}}{\text{lbmol}}} = 54.61 \frac{\text{ft} \cdot \text{lbf}}{\text{lbm} \cdot °\text{R}}$$

$$R_{\text{mix},sp} = 0.0702 \frac{\text{Btu}}{\text{lbm} \cdot °\text{R}}$$

C-2.3.4 Specific Heats

(a) Calculate specific heats at the specified inlet conditions using an empirical formula for determining c_p from static temperature in °R. Note that because ambient and inlet temperature and fraction of water are equal, the specific heat at ambient and inlet will be equal.

$$\bar{c}_{p,da} \frac{\text{Btu}}{\text{lbmol} \cdot °\text{R}} = \left[3.647458 - 7.08954 \cdot 10^{-4} \cdot °\text{R} + 9.41274 \cdot 10^{-7} \cdot °\text{R}^2 - 2.54339 \cdot 10^{-10} \cdot °\text{R}^3\right] \cdot \overline{\text{R}}$$

$$\bar{c}_{p,vp} \frac{\text{Btu}}{\text{lbmol} \cdot °\text{R}} = \left[4.05380 - 5.1711 \cdot 10^{-4} \cdot °\text{R} + 1.05975 \cdot 10^{-6} \cdot °\text{R}^2 - 2.92781 \cdot 10^{-10} \cdot °\text{R}^3\right] \cdot \overline{\text{R}}$$

(b) Calculate c_p for each gas at the specified inlet temperature.

$$\bar{c}_{p,da,i,sp} = \left[3.647458 - 7.08954 \cdot 10^{-4} \cdot 559.6 + 9.41274 \cdot 10^{-7} \cdot 559.67^2 - 2.54339 \cdot 10^{-10} \cdot 559.67^3\right] \cdot 1.98588$$

$$\bar{c}_{p,da,i,sp} = 6.9524 \frac{\text{Btu}}{\text{lbmol} \cdot °\text{R}}$$

$$\bar{c}_{p,vp,i,sp} = \left[4.05380 - 5.1711 \cdot 10^{-4} \cdot 559.6 + 1.05975 \cdot 10^{-6} \cdot 559.67^2 - 2.92781 \cdot 10^{-10} \cdot 559.67^3\right] \cdot 1.98588$$

$$\bar{c}_{p,vp,i,sp} = 8.0239 \frac{\text{Btu}}{\text{lbmol} \cdot {}^\circ\text{R}}$$

(c) Calculate the specific heat of the mixture at inlet conditions based on the proportions of each component.

$$c_{p,\text{mix},i,sp} = \frac{(1 - x_{v,sp}) \cdot c_{p,da,sp} + x_{v,sp} \cdot c_{p,vp,sp}}{\text{MW}_{\text{mix},sp}}$$

$$c_{p,\text{mix},i,sp} = \frac{(1 - 0.0613) \cdot 6.9524 + 0.0613 \cdot 8.0239}{28.30}$$

$$c_{p,\text{mix},i,sp} = 0.2480 \frac{\text{Btu}}{\text{lbm} \cdot {}^\circ\text{R}}$$

(d) To complete this step, calculate κ, the isentropic exponent (ratio of specific heats), at specified inlet conditions.

$$\kappa_{sp} = \frac{c_{p,\text{mix},i,sp}}{c_{p,\text{mix},i,sp} - \text{R}_{\text{mix},sp}} = \frac{0.2480 \frac{\text{Btu}}{\text{lbm} \cdot {}^\circ\text{R}}}{0.2480 \frac{\text{Btu}}{\text{lbm} \cdot {}^\circ\text{R}} - 0.0702 \frac{\text{Btu}}{\text{lbm} \cdot {}^\circ\text{R}}} = 1.3946$$

C-3 STEP 2: DETERMINE BLOWER TYPE

C-3.1 Determine Blower Characteristics

Blower characteristics shall be determined and installation characteristics shall be tested. The test installation of this example uses a screw-type PD blower package that includes

(a) blower, rated 3,200 ft^3/min at 60 Hz

  (1) min. blower speed 3,550 rpm, max. blower speed 7100 rpm

(b) motor, rated 150 hp, 3,550 rpm at full load and 60 Hz, 185 FLA

  (1) min. motor speed 1,775 rpm @ 30 Hz

(c) v-belt drive connection between blower and motor, with automatic belt tensioning system, 2:1 ratio blower:motor

(d) variable frequency drive, rated 480 VAC, 60 Hz, 3-phase input power, 125 kW max. input power

(e) flanged pipe inlet with external filter

(f) flanged pipe discharge

(g) sound enclosure

(h) control panel powered from motor power connections using internal control transformer

(i) max. discharge temperature = 300°F

In this test installation, mass flow rate is measured by orifice with pressure and temperature compensation. The test inlet piping is Schedule 40 12 in.-pipe with an 11.938 in. inner diameter and a flow channel cross-sectional area (A_i) of 0.777 ft^2. The test discharge piping is Schedule 40 10 in.-pipe with a 10.020 in. inner diameter and a flow channel cross-sectional area (A_d) of 0.548 ft^2.

During testing, the blower speed shall be adjusted to provide the inlet volumetric flow rate equivalent to the specified flow rate. The restriction on the discharge of the blower shall be adjusted to provide the required pressure ratio.

The package air inlet boundary for the test shall be defined as the flange provided for field piping connection.

C-3.2 Document Components

Process and fluid components shall be determined and documented. See para 3-5.2(a). Table 3-5.2-1 is a test-specific checklist intended to be prepared and agreed upon between the parties to a test. Table C-3.2-1 is that list completed per the test installation in this Appendix.

Electric power-related components shall be determined and documented. See para 3-5.2(b). Table 3-5.2-2 is a test-specific checklist intended to be prepared and agreed upon between the parties to a test. Table C-3.2-2 is that list completed per the test installation in this Appendix.

Table C-3.2-1 Process and Fluid Components

	Included in Performance Boundary		
Component	**Included in Test**	**Adjusted by Calculation**	**Not Required**
Inlet filter	X	...	...
Inlet silencer	X	...	...
Discharge silencer	X	...	...
Inlet isolation valve	...	...	X
Throttling valve	...	...	X
After cooler	...	...	X
Misc. pipe and fittings	...	X	...
Inlet air cooler	...	...	X
Discharge check valve	X	...	...
Discharge isolation valve	...	...	X
Enclosure doors or panel openings	X	...	...
Estimated system inlet press drop	...	...	X

Table C-3.2-2 Electric Power-Related Components

	Included in Performance Boundary		
Component	**Included in Test**	**Adjusted by Calculation**	**Not Required**
Drive motor	X	...	...
Motor cooling fan(s)	X	...	...
Magnetic bearing and controller	...	...	X
Bearing cooling fan(s)	...	...	X
Coolant pumps	...	...	X
Lubrication pumps and accessories	X	...	...
Heat exchanger fans	...	...	X
Package cooling fan	X	...	...
VFD	X	...	...
VFD line-side power-conditioning equipment	X	...	...
VFD load-side power-conditioning equipment	X	...	...
Eddy current or variable-speed clutch	...	...	X
Operation control panel(s)	X	...	...
Power/isolation transformers and power supply	...	X	...
Power conditioner	...	...	X
Blower and motor water conditioning or chilling	...	...	X
VFD water conditioning or chilling	...	...	X

C-4 STEP 3: RUN PRETEST CALCULATIONS

C-4.1 Pretest Calculations for Specified Design Point(s)

Calculate the specified mass flow rate and pressure ratio and the required inlet flow rate at test based on total temperature and pressure.

C-4.1.1 Ambient Density and Flow Rates. Calculate the ambient density and volumetric and mass flow rates.

$$\rho_{a,sp} = \frac{p_{a,sp}}{R_{\text{mix},sp} \cdot T_{a,sp}} = \frac{13.95\ \text{psia} \cdot 144\frac{\text{in}^2}{\text{ft}^2}}{54.61\frac{\text{ft} \cdot \text{lbf}}{\text{lbm} \cdot {}^\circ\text{R}} \cdot 559.67\ {}^\circ\text{R}} = 0.0657\frac{\text{lbm}}{\text{ft}^3}$$

$$q_{sp,\text{std}} = 2{,}500\ \text{SCFM}$$

$$q_{v,a,sp} = q_{sp,\text{std}} \cdot \frac{p_{\text{std}} - p_{sv,\text{std}} \cdot \text{RH}_{\text{std}}}{p_{a,sp} - p_{vp,sp}} \cdot \frac{T_{a,sp}}{T_{\text{std}}}$$

$$q_{v,a,sp} = 2{,}500 \cdot \frac{14.7 - 0.3390 \cdot 0.36}{13.95 - 0.8546} \cdot \frac{559.67}{527.67} = 2{,}952\frac{\text{ft}^3}{\text{min}}$$

$$q_{m,sp} = q_{v,a,sp} \cdot \rho_{a,sp} = 2{,}952 \cdot 0.0657 = 194.02\frac{\text{lbm}}{\text{min}}$$

C-4.1.2 Inlet Density. Estimate the inlet density at the specified static conditions.

$$\rho_{i,sp,\text{static}} = \frac{p_{i,sp,\text{static}}}{R_{\text{mix},sp} \cdot T_{i,sp,\text{static}}} = \frac{13.80\ \text{psia} \cdot 144\frac{\text{in.}^2}{\text{ft}^2}}{54.61\frac{\text{ft} \cdot \text{lbf}}{\text{lbm} \cdot {}^\circ\text{R}} \cdot 559.67{}^\circ\text{R}} = 0.06502\frac{\text{lbm}}{\text{ft}^3}$$

C-4.1.3 Discharge Air Temperature. Estimate the discharge air temperature for use in calculating discharge properties at specified conditions (see Nonmandatory Appendix J). Use an estimated efficiency and κ.

$$\eta_{\text{est}} = 65\%$$

$$T_{d,sp,\text{static,est}} = T_{i,sp,\text{static}} + \frac{\left[\left(\frac{p_{d\ sp,\text{static}}}{p_{i,sp,\text{static}}}\right)^{\left(\frac{\kappa_{\text{mix,std}} - 1}{\kappa_{\text{mix,std}}}\right)} - 1\right] \cdot T_{i,sp,\text{static}}}{\eta_{\text{est}}}$$

$$T_{d,sp,\text{static,est}} = 559.67 + \frac{\left[\left(\frac{22.45}{13.80}\right)^{\left(\frac{1.3996-1}{1.3996}\right)} - 1\right] \cdot 559.67}{0.65}$$

$$T_{d,sp,\text{static,est}} = 6.88.01{}^\circ\text{R} = 228.34{}^\circ\text{F}$$

C-4.1.4 Discharge Density. Estimate the discharge density at the specified static conditions.

$$\rho_{d,sp,\text{static}} = \frac{p_{d,sp,\text{static}}}{R_{\text{mix},sp} \cdot T_{d,sp,\text{static,est}}} = \frac{22.45\ \text{psia} \cdot 144 \frac{\text{in.}^2}{\text{ft}^2}}{54.61 \frac{\text{ft} \cdot \text{lbf}}{\text{lbm} \cdot {}^\circ\text{R}} \cdot 688.01^\circ\text{R}}$$

$$\rho_{d,sp,\text{static}} = 0.08605 \frac{\text{lbm}}{\text{ft}^3}$$

C-4.1.5 Area of Pipes. Calculate the area of the inlet and discharge pipes at the specified conditions.

$$A_{i,sp} = \frac{\pi \cdot D_{i,sp}^2}{4} = \frac{\pi \cdot \left(\frac{13.124}{12}\right)^2}{4} = 0.939\ \text{ft}^2$$

$$A_{d,sp} = \frac{\pi \cdot D_{d,sp}^2}{4} = \frac{\pi \cdot \left(\frac{11.938}{12}\right)^2}{4} = 0.777\ \text{ft}^2$$

C-4.1.6 Air Velocity at Specified Conditions. Calculate the velocity of the air at the specified inlet and discharge conditions. The difference between total and static pressure is negligible for determining velocity head.

$$V_{i,sp} = \frac{q_{m,sp}}{\rho_{i,sp,\text{static}} \cdot A_{i,sp}} = \frac{194.02 \frac{\text{lbm}}{\text{min}} \cdot \frac{\text{min}}{60\ \text{sec}}}{0.06502 \frac{\text{lbm}}{\text{ft}^3} \cdot 0.939\ \text{ft}^2} = 52.94 \frac{\text{ft}}{\text{sec}} = 3{,}176 \frac{\text{ft}}{\text{min}}$$

$$V_{d,sp} = \frac{q_{m,sp}}{\rho_{d,sp,\text{static}} \cdot A_{d,sp}} = \frac{194.02 \frac{\text{lbm}}{\text{min}} \cdot \frac{\text{min}}{60\ \text{sec}}}{0.08605 \frac{\text{lbm}}{\text{ft}^3} \cdot 0.777\ \text{ft}^2} = 48.35 \frac{\text{ft}}{\text{sec}} = 2{,}901 \frac{\text{ft}}{\text{min}}$$

C-4.1.7 Velocity Pressure at Inlet.

(a) Calculate the velocity pressure at specified inlet conditions.

$$p_{v,i,sp} = \frac{V_{i,sp}^2 \cdot \rho_{i,sp,\text{static}}}{2 g_c} = \frac{\left(52.94 \frac{\text{ft}}{\text{sec}}\right)^2 \cdot 0.06502 \frac{\text{lbm}}{\text{ft}^3}}{2 \cdot 32.1741 \frac{\text{lbm} \cdot \text{ft}}{\text{lbf} \cdot \text{sec}^2} \cdot \frac{144\ \text{in.}^2}{\text{ft}^2}} = 0.0197\ \text{psia}$$

(b) Calculate the total pressure at specified inlet conditions.

$$p_{i,sp} = p_{i,sp,\text{static}} + p_{v,i,sp} = 13.80\ \text{psia} + 0.0197\ \text{psia} = 13.820\ \text{psia}$$

(c) Assuming a recovery factor for temperature transmitters of $r_f = 0.65$, calculate the total temperature at specified inlet conditions.

$$T_{i,sp} = T_{i,sp,\text{static}} + \left(1 - r_f\right) \cdot \frac{V_{i,sp}^2}{2 \cdot c_{p,\,\text{mix},i,sp}}$$

$$T_{i,sp} = 559.67 + (1 - 0.65) \cdot \frac{52.94^2}{2 \cdot 0.2480 \frac{\text{Btu}}{\text{lbm} \cdot {}^\circ\text{R}} \cdot 32.1741 \frac{\text{lbm} \cdot \text{ft}}{\text{lbf} \cdot \text{sec}^2} \cdot 778.17 \frac{\text{ft} \cdot \text{lbf}}{\text{lbm} \cdot {}^\circ\text{R}}}$$

$$T_{i,sp} = 559.75^\circ\text{R} = 100.08^\circ\text{F}$$

C-4.1.8 Velocity Pressure at Discharge.

(a) Calculate the velocity pressure at specified discharge conditions.

$$p_{v,d,sp} = \frac{V_{d,sp}^2 \cdot \rho_{d,sp,\text{static}}}{2g_c} = \frac{\left(48.35\frac{\text{ft}}{\text{sec}}\right)^2 \cdot 0.08605\frac{\text{lbm}}{\text{ft}^3}}{2 \cdot 32.1741\frac{\text{lbm} \cdot \text{ft}}{\text{lbf} \cdot \text{sec}^2} \cdot \frac{144\ \text{in.}^2}{\text{ft}^2}} = 0.0217\ \text{psia}$$

(b) Calculate the total pressure at specified discharge conditions.

$$p_{d,sp} = p_{d,sp,\text{static}} + p_{v,d,sp} = 22.45\ \text{psia} + 0.02\ \text{psia} = 22.47\ \text{psia}$$

NOTE: Since discharge temperature is estimated, it is superfluous to recalculate discharge total temperature.

$$T_{d,sp} = T_{d,sp,\text{static,est}} = 688.01°\text{R} = 228.34°\text{F}$$

C-4.1.9 Inlet Volumetric Flow Rate. Calculate the inlet volumetric flow rate (ft^3/min) required at test to produce the specified mass flow rate of dry air at the specified total conditions.

$$q_{v,t,sp} = q_{sp,\text{std}} \cdot \frac{p_{\text{std}} - p_{sv,\text{std}} \cdot \text{RH}_{\text{std}}}{p_{a,sp} - p_{vp,sp}} \cdot \frac{T_{i,sp}}{T_{\text{std}}} \cdot \frac{p_{a,sp}}{p_{i,sp}}$$

$$q_{v,t,sp} = 2{,}500 \cdot \frac{14.7 - 0.3390 \cdot 0.36}{13.95 - 0.8546} \cdot \frac{559.74}{527.67} \cdot \frac{13.95}{13.818} = 2{,}980\frac{\text{ft}^3}{\text{min}}$$

C-4.1.10 Required Pressure Ratio. Calculate the required pressure ratio for testing from the specified static pressures.

$$r_{p,sp} = \frac{p_{d,sp}}{p_{i,sp}}$$

$$r_{p,sp} = \frac{22.47}{13.818} = 1.6261$$

C-5 STEP 4: PREPARE FOR TEST

C-5.1 Verify Mechanical Readiness (as Applicable)

Mechanical readiness for the test shall be verified, as illustrated in Figure C-5.1-1. Bearing and gear lubrication, belt tensioning system, and piping connections shall be evaluated.

C-5.2 Verify Safety Considerations

Refer to para. 3-5.1 for a safety overview. Belt guards, mechanical systems, wiring, and electric systems shall be evaluated. Safety precautions shall be in place, and hearing and eye protection shall be provided.

C-5.3 Run Preliminary Tests

Preliminary test runs shall be performed as detailed in para. 3-2.2 and in accordance with the test operation procedures explained in subsection 3-5.

C-5.4 Check Instrumentation

Instruments shall be configured per Section 4, and instrument calibration records verified per para. 4-1.2.

NOTE: All measurements are to be the average of three consecutive readings. See para. 3-5.5.

C-5.5 Measure Ambient Conditions

Following completion of mechanical and instrumentation checks, the ambient conditions shall be measured. The results from the test installation are shown in Table C-5.5-1.

Figure C-5.1-1 PD Blower Testing

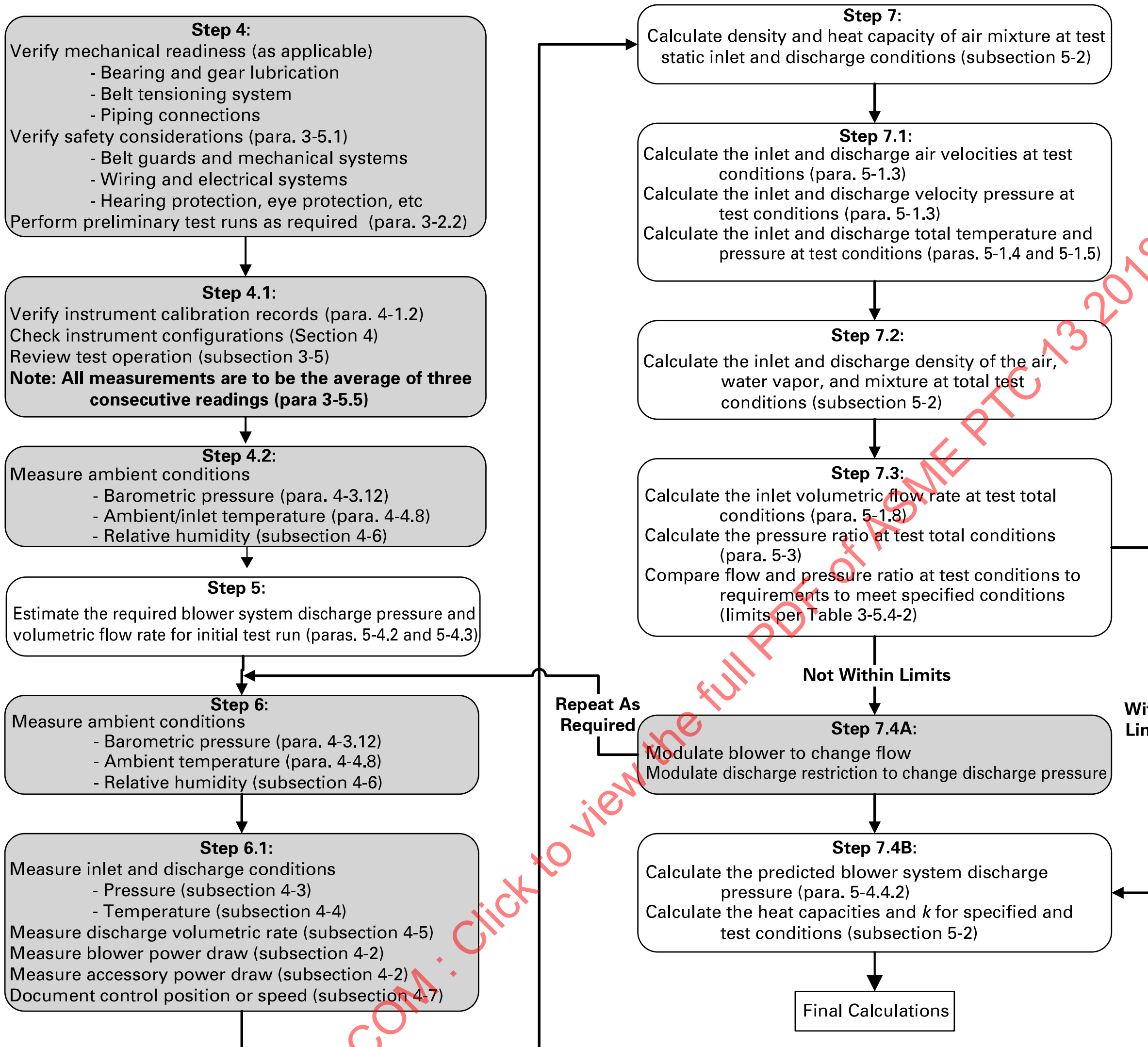


Table C-5.5-1 Ambient Conditions at Test

Parameter, Symbol	Value
Ambient temperature, $T_{i,t}$	78.2°F = 537.87°R
Ambient (barometric) pressure, $p_{amb,t}$	14.65 psia
Relative humidity, RH_t	47.5%

C-6 STEP 5: ESTIMATE DISCHARGE PRESSURE/FLOW RATE FOR TEST RUN

C-6.1 Estimate Inlet Pressure and Required Discharge Pressure at Test

$$\Delta p_{i,t,\text{est}} = 0.05 \text{ psi}$$

$$p_{i,t,\text{static,est}} = p_{a,t} - \Delta p_{i,t,\text{est}} = 14.65 - 0.05 = 14.60 \text{ psi}$$

$$p_{d,t,\text{est}} = p_{i,t,\text{static,est}} \cdot r_{p,sp} = 14.60 \cdot 1.6261 = 23.74 \text{ psia}$$

$$p_{d,t,\text{est},ga} = p_{d,t,\text{est}} - p_{a,t} = 23.75 - 14.65 = 9.09 \text{ psig}$$

C-6.2 Estimate Inlet Properties at Test Conditions

$$\beta_{a,t} = \frac{-7{,}202.2367}{537.87 - 70.431} = -15.4079$$

$$p_{sv,a,t} = 2{,}349.081 \cdot 10^3 \cdot 2.71828^{-15.4079} = 0.4779 \text{ psia}$$

$$p_{vp,a,t} = \text{RH}_{a,t} \cdot p_{vs,a,t} = 0.475 \cdot 0.4779 = 0.2270 \text{ psia}$$

$$x_{vp,t} = \frac{0.2270}{14.65} = 0.0155$$

$$\text{MW}_{a,t} = (1 - 0.0155) \cdot 28.97 + 0.0155 \cdot 18.015 = 28.80 \frac{\text{lbm}}{\text{lbmol}}$$

C-6.3 Calculate Specific-Mixture Gas Constant

$$R_{\text{mix},a,t} = \frac{1{,}545.35 \dfrac{\text{ft} \cdot \text{lbf}}{\text{lbmol} \cdot {}^\circ\text{R}}}{28.80 \dfrac{\text{lbm}}{\text{lbmol}}} = 53.66 \frac{\text{ft} \cdot \text{lbf}}{\text{lbm} \cdot {}^\circ\text{R}} = 0.0690 \frac{\text{Btu}}{\text{lbm} \cdot {}^\circ\text{R}}$$

C-6.4 Calculate Density at Test Static Inlet Conditions

$$\rho_{\text{mix},i,t,\text{static,est}} = \frac{14.60 \text{ psi} \cdot 144 \dfrac{\text{in.}^2}{\text{ft}^2}}{53.66 \dfrac{\text{ft} \cdot \text{lbf}}{\text{lbm} \cdot {}^\circ\text{R}} \cdot 537.87^\circ\text{R}} = 0.0728 \frac{\text{lbm}}{\text{ft}^3}$$

C-6.5 Calculate Initial Target Test Mass Flow Rate

$$q_{m,\text{t},\text{est}} = q_{v,t,sp} \cdot \rho_{\text{mix},i,t,\text{static,est}}$$

$$q_{m,t,\text{est}} = 2978 \cdot 0.0728 = 217 \frac{\text{lbm}}{\text{min}}$$

C-7 STEP 6: MEASURE CONDITIONS

Following the initial test run, ambient, inlet, and discharge parameters shall be measured. Mass flow rate and system power draw shall be measured.

The results from this example are shown in Table C-7-1.

Table C-7-1 Results of Initial Test Run

Parameter, Symbol	Value
Ambient temperature, $T_{i,t}$	78.2°F = 537.87°R
Ambient (barometric) pressure, $p_{a,t}$	14.65 psia
Relative humidity, RH_t	47.5%
Inlet temperature, $T_{i,t,\text{static}}$	78.2°F = 537.87°R
Discharge temperature, $T_{d,t,\text{static}}$	204.1°F = 663.77°R
Inlet pressure, $p_{i,t,\text{static}}$	14.58 psia
Discharge pressure (gauge), $p_{d,t,\text{static},ga}$	9.18 psig
Discharge pressure (static), $p_{d,t,\text{static}}$	23.83 psia
Discharge mass flow rate, $q_{m,t}$	219.4 lbm/min
Motor speed	3339 rpm
Blower speed	6,678 rpm
System electric power draw, P_t	120.3 kW

C-8 STEP 7: CALCULATE PROPERTIES

C-8.1 Calculate Properties at Static Inlet Conditions

C-8.1.1 Density. Calculate the inlet and discharge density at test static conditions.

$$\rho_{\text{mix},i,t,\text{static}} = \frac{p_{i,t,\text{static}}}{R_{\text{mix},a,t} \cdot T_{i,t,\text{static}}} = \frac{14.58\ \text{psi} \cdot 144\dfrac{\text{in.}^2}{\text{ft}^2}}{53.66\dfrac{\text{ft} \cdot \text{lbf}}{\text{lbm} \cdot {}^\circ\text{R}} \cdot 537.87^\circ\text{R}} = 0.0727\frac{\text{lbm}}{\text{ft}^3}$$

$$\rho_{\text{mix},d,t,\text{static}} = \frac{p_{d,t,\text{static}}}{R_{\text{mix},a,t} \cdot T_{d,t,\text{static}}} = \frac{23.83\ \text{psi} \cdot 144\dfrac{\text{in.}^2}{\text{ft}^2}}{53.66\dfrac{\text{ft} \cdot \text{lbf}}{\text{lbm} \cdot {}^\circ\text{R}} \cdot 663.77^\circ\text{R}} = 0.0963\frac{\text{lbm}}{\text{ft}^3}$$

C-8.1.2 Specific Heats. Calculate the inlet and discharge specific heats at test static conditions. These values shall be used to calculate total temperatures and pressures.

$$\bar{c}_{p,vp,i,t} = \left[4.05380 - 5.1711 \cdot 10^{-4} \cdot 537.99 + 1.05975 \cdot 10^{-6} \cdot 537.99^2 - 2.92781 \cdot 10^{-10} \cdot 537.99^3\right] \cdot 1.98588$$

$$\bar{c}_{p,vp,i,t} = 8.0164\frac{\text{Btu}}{\text{lbmol} \cdot {}^\circ\text{R}}$$

$$\bar{c}_{p,da,i,t} = \left[3.647458 - 7.08954 \cdot 10^{-4} \cdot 537.99 + 9.41274 \cdot 10^{-7} \cdot 537.99^2 - 2.54339 \cdot 10^{-10} \cdot 537.99^3\right] \cdot 1.98588$$

$$\bar{c}_{p,da,i,t} = 6.9483\frac{\text{Btu}}{\text{lbmol} \cdot {}^\circ\text{R}}$$

$$c_{p,\text{mix},i,t} = \frac{(1 - 0.0155) \cdot 6.9483 + 0.0155 \cdot 8.0164}{28.80}$$

$$c_{p,\text{mix},i,t} = 0.2418\frac{\text{Btu}}{\text{lbm} \cdot {}^\circ\text{R}}$$

$$\bar{c}_{p,vp,d,t} = \left[4.05380 - 5.1711 \cdot 10^{-4} \cdot 663.77 + 1.05975 \cdot 10^{-6} \cdot 663.77^2 - 2.92781 \cdot 10^{-10} \cdot 663.77^3\right] \cdot 1.98588$$

$$\bar{c}_{p,vp,d,t} = 8.1259 \frac{\text{Btu}}{\text{lbmol} \cdot {}^\circ\text{R}}$$

$$\bar{c}_{p,da,d,t} = \left[3.647458 - 7.08954 \cdot 10^{-4} \cdot 663.77 + 9.41274 \cdot 10^{-7} \cdot 663.77^2 - 2.54339 \cdot 10^{-10} \cdot 663.77^3\right] \cdot 1.98588$$

$$\bar{c}_{p,da,d,t} = 6.9847 \frac{\text{Btu}}{\text{lbmol} \cdot {}^\circ\text{R}}$$

$$c_{p,\text{mix},d,t} = \frac{(1 - 0.0155) \cdot 6.9847 + 0.0155 \cdot 8.1259}{28.80}$$

$$c_{p,\text{mix},d,t} = 0.2431 \frac{\text{Btu}}{\text{lbm} \cdot {}^\circ\text{R}}$$

C-8.2 Calculate Thermodynamic Properties at Total Test Inlet and Discharge Conditions

C-8.2.1 Area of Pipes. Calculate the area of the inlet and discharge pipes at test conditions.

$$A_{i,t} = \frac{\pi \cdot D_{i,t}^2}{4} = \frac{\pi \cdot \left(\frac{11.938}{12}\right)^2}{4} = 0.777 \text{ ft}^2$$

$$A_{d,t} = \frac{\pi \cdot D_{d,t}^2}{4} = \frac{\pi \cdot \left(\frac{10.020}{12}\right)^2}{4} = 0.548 \text{ ft}^2$$

C-8.2.2 Velocity of Air. Calculate the velocity of the air at test inlet and discharge conditions.

$$V_{i,t} = \frac{w_t}{\rho_{\text{mix},i,t,\text{static}} \cdot A_{i,t}} = \frac{219.4 \frac{\text{lbm}}{\text{min}} \cdot \frac{\text{min}}{60 \text{ sec}}}{0.07274 \frac{\text{lbm}}{\text{ft}^3} \cdot 0.7773 \text{ ft}^2} = 64.67 \frac{\text{ft}}{\text{sec}} = 3{,}880 \frac{\text{ft}}{\text{min}}$$

$$V_{d,t} = \frac{w_t}{\rho_{\text{mix},d,t,\text{static}} \cdot A_{d,t}} = \frac{219.4 \frac{\text{lbm}}{\text{min}} \cdot \frac{\text{min}}{60 \text{ sec}}}{0.09634 \frac{\text{lbm}}{\text{ft}^3} \cdot 0.5476 \text{ ft}^2} = 69.31 \frac{\text{ft}}{\text{sec}} = 4{,}159 \frac{\text{ft}}{\text{min}}$$

C-8.2.3 Inlet Velocity Pressure. Calculate the velocity pressure at test inlet conditions.

$$p_{v,i,t} = \frac{\left(64.67 \frac{\text{ft}}{\text{sec}}\right)^2 \cdot 0.0727 \frac{\text{lbm}}{\text{ft}^3}}{2 \cdot 32.1741 \frac{\text{lbm} \cdot \text{ft}}{\text{lbf} \cdot \text{sec}^2} \cdot \frac{144 \text{ in.}^2}{\text{ft}^2}} = 0.0328 \text{ psia}$$

C-8.2.4 Inlet Total Pressure. Calculate the total pressure at test inlet conditions.

$$p_{i,t} = p_{i,sp,\text{static}} + p_{v,i,sp} = 14.58 \text{ psia} + 0.0328 \text{ psia} = 14.613 \text{ psia}$$

C-8.2.5 Inlet Total Temperature. Calculate the total temperature at test inlet conditions.

$$T_{i,t} = 537.87 + (1 - 0.65) \cdot \frac{\left(64.67 \frac{\text{ft}}{\text{sec}}\right)^2}{2 \cdot 0.2431 \frac{\text{Btu}}{\text{lbm} \cdot {}^\circ\text{R}} \cdot 32.1741 \frac{\text{lbm} \cdot \text{ft}}{\text{lbf} \cdot \text{sec}^2} \cdot 778.17 \frac{\text{ft} \cdot \text{lbf}}{\text{lbm} \cdot {}^\circ\text{R}}}$$

$$T_{i,t} = 537.99{}^\circ\text{R} = 78.32{}^\circ\text{F}$$

C-8.2.6 Discharge Velocity Pressure. Calculate the velocity pressure at test discharge conditions.

$$p_{v,d,t} = \frac{V_{d,t}^2 \cdot \rho_{\text{mix},d,t,\text{static}}}{2g_c} = \frac{\left(69.31\frac{\text{ft}}{\text{sec}}\right)^2 \cdot 0.0963\frac{\text{lbm}}{\text{ft}^3}}{2\cdot 32.1741\frac{\text{lbm}\cdot\text{ft}}{\text{lbf}\cdot\text{sec}^2}\cdot\frac{144\text{ in.}^2}{\text{ft}^2}} = 0.0499\text{ psia}$$

C-8.2.7 Discharge Total Pressure. Calculate the total pressure at test discharge conditions.

$$p_{d,t} = p_{d,t,\text{static}} + p_{v,d,t} = 23.83\text{ psia} + 0.0499\text{ psia} = 23.88\text{ psia}$$

C-8.2.8 Discharge Total Temperature. Calculate the total temperature at test discharge conditions.

$$T_{d,t} = T_{d,t,\text{static}} + (1 - r_f)\cdot\frac{V_{d,t}^2}{2\cdot c_{p,\text{mix},d,t,\text{static}}}$$

$$T_{d,t} = 663.77 + (1 - 0.65)\cdot\frac{\left(69.31\frac{\text{ft}}{\text{sec}}\right)^2}{2\cdot 0.2444\frac{\text{Btu}}{\text{lbm}\cdot{}^\circ\text{R}}\cdot 32.1741\frac{\text{lbm}\cdot\text{ft}}{\text{lbf}\cdot\text{sec}^2}\cdot 778.17\frac{\text{ft}\cdot\text{lbf}}{\text{lbm}\cdot{}^\circ\text{R}}}$$

$$T_{d,t} = 663.91^\circ\text{R} = 204.24^\circ\text{F}$$

C-8.3 Calculate Inlet/Discharge Density of Mixture at Total Test Conditions

C-8.3.1 Density. Calculate the density at test total inlet and discharge conditions.

$$\rho_{\text{mix},i,t} = \frac{14.61\text{ psi}\cdot 144\frac{\text{in.}^2}{\text{ft}^2}}{53.66\frac{\text{ft}\cdot\text{lbf}}{\text{lbm}\cdot{}^\circ\text{R}}\cdot 537.99^\circ\text{R}} = 0.07289\frac{\text{lbm}}{\text{ft}^3}$$

$$\rho_{\text{mix},d,t} = \frac{23.88\text{ psi}\cdot 144\frac{\text{in.}^2}{\text{ft}^2}}{53.66\frac{\text{ft}\cdot\text{lbf}}{\text{lbm}\cdot{}^\circ\text{R}}\cdot 663.91^\circ\text{R}} = 0.09653\frac{\text{lbm}}{\text{ft}^3}$$

C-8.4 Calculate Flow Rate/Pressure Ratio at Test and Compare to Allowable Deviations

C-8.4.1 Volumetric Flow Rate. Calculate the actual test inlet volumetric flow rate at test conditions.

$$q_{v,i,t} = \frac{q_{m,t}}{\rho_{\text{mix},i,t}} = \frac{219.4\cdot\frac{\text{lbm}}{\text{min}}}{0.07289\frac{\text{lbm}}{\text{ft}^3}} = 3{,}010\frac{\text{ft}^3}{\text{min}}$$

Calculate the deviation between specified and test flow rate.

$$\text{Deviation} = \frac{q_{v,i,t}}{q_{v,t,sp}}\cdot 100 = \frac{3{,}010}{2{,}980}\cdot 100 = 101.0$$

The deviation conforms to the range limit of 98% to 102% established in Table 3-5.4-2 for variable speed blowers; it is within allowable limits.

C-8.4.2 Pressure Ratio. Calculate the actual test pressure ratio from static pressures.

$$r_{p,t} = \frac{p_{d,t,\text{static}}}{p_{i,t,\text{static}}}$$

$$r_{p,t} = \frac{23.88}{14.61} = 1.634$$

Calculate the deviation between specified and test pressure ratio.

$$\text{Deviation} = \frac{r_{p,t}}{r_{p,sp}} \cdot 100 = \frac{1.634}{1.626} \cdot 100 = 100.5$$

The deviation conforms to the range limit of 100% to 102% established in Table 3-5.4-2 for variable speed blowers; it is within allowable limits.

NOTE: Additional modulation per para. C-8.5 is not required if deviations are within limits.

C-8.5 Estimate Thermodynamic Properties Based on Test Blower Performance

Calculate the predicted discharge pressure at specified conditions and estimate the average thermodynamic properties at test and specified conditions based on test blower performance.

C-8.5.1 Calculate Predicted Discharge Pressure. Calculate the predicted discharge pressure at the specified conditions. Gauge pressure shall be static to match field measurement techniques.

$$p_{d,pr} = r_{p,t} \cdot p_{i,sp} = 1.634 \cdot 13.82 = 22.58 \text{ psig}$$

$$p_{d,pr,\text{static},ga} = p_{d,pr} - p_{v,d,sp} - p_{a,sp}$$

$$p_{d,pr,ga} = 22.58 - 0.02 - 13.95 = 8.61 \text{ psia}$$

C-8.5.2 Calculate Isentropic Exponent. Calculate κ, the isentropic exponent (ratio of specific heats), at the test inlet conditions.

$$\kappa_t = \frac{0.2418 \frac{\text{Btu}}{\text{lbm} \cdot {}^\circ\text{R}}}{0.2418 \frac{\text{Btu}}{\text{lbm} \cdot {}^\circ\text{R}} - 0.0690 \frac{\text{Btu}}{\text{lbm} \cdot {}^\circ\text{R}}} = 1.3989$$

C-9 STEP 8: RUN FINAL CALCULATIONS

Final calculations for the parameters described herein shall be run, as outlined in Figure C-9-1.

C-9.1 Calculate Predicted Air Flow Rate

Calculate the predicted air flow rate at specified conditions.

C-9.1.1 Inlet Volumetric Flow Rate. Calculate predicted inlet volumetric flow rate.

$$q_{v,i,pr} = q_{v,i,t} = 3{,}010 \frac{\text{ft}^3}{\text{min}}$$

C-9.1.2 Mass Flow Rate. Calculate the predicted mass flow rate as SCFM, representing the equivalent mass of dry air.

$$q_{pr,\text{std}} = q_{v,i,pr} \cdot \frac{p_{a,sp} - p_{vp,sp}}{p_{\text{std}} - p_{sv,\text{std}} \cdot \text{RH}_{\text{std}}} \cdot \frac{T_{\text{std}}}{T_{i,sp}} \cdot \frac{p_{i,sp}}{p_{a,sp}}$$

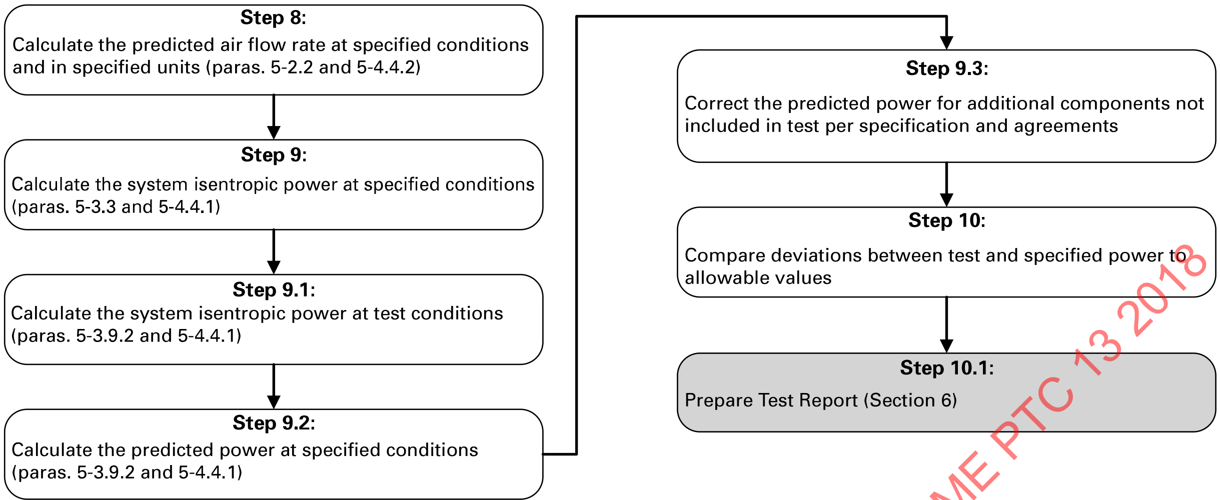
$$q_{pr,\text{std}} = 3{,}010 \cdot \frac{13.95 - 0.8546}{14.7 - 0.34 \cdot 0.36} \cdot \frac{527.67}{559.74} \cdot \frac{13.82}{13.95} = 2{,}525 \text{ SCFM}$$

C-9.2 Calculate Isentropic Power

C-9.2.1 Isentropic Power at Specified Conditions

$$P_{s,sp} = q_{m,sp} \cdot \frac{\kappa_{sp}}{\kappa_{sp} - 1} \cdot R_{\text{mix},sp} \cdot T_{i,sp} \cdot \left[r_{p,sp}^{\left(\frac{\kappa_{sp}}{\kappa_{sp}-1}\right)} - 1 \right] \cdot \frac{1 \text{ hp}}{33{,}000 \frac{\text{ft} \cdot \text{lbf}}{\text{min}}}$$

Figure C-9-1 Final Calculations



$$P_{s.sp} = 194.02 \cdot \frac{1.3946}{1.3946 - 1} \cdot 54.61 \cdot 559.75 \cdot \left[1.6261^{\left(\frac{1.3946-1}{1.3946}\right)} - 1 \right] \cdot \frac{1}{33{,}000}$$

$$P_{s,sp} = 93.66 \text{ hp}$$

$$93.66 \text{ hp} \cdot \frac{1 \text{ kW}}{1.341 \text{ hp}} = 69.84 \text{ kW}$$

C-9.2.2 Isentropic Power at Test Conditions

$$P_{s,t} = q_{m,t} \cdot \frac{\kappa_t}{\kappa_t - 1} \cdot R_{mix,a,t} \cdot T_{i,t} \cdot \left[r_{p,t}^{\left(\frac{\kappa_t}{\kappa_t - 1}\right)} - 1 \right] \cdot \frac{1 \text{ hp}}{33{,}000 \frac{\text{ft} \cdot \text{lbf}}{\text{min}}}$$

$$P_{s,t} = 219.4 \cdot \frac{1.3989}{1.3989 - 1} \cdot 53.66 \cdot 537.99 \cdot \left[1.6342^{\left(\frac{1.3989-1}{1.3989}\right)} - 1 \right] \cdot \frac{1}{33{,}000}$$

$$P_{s,t} = 101.18 \text{ hp}$$

$$101.18 \text{ hp} \cdot \frac{1 \text{ kW}}{1.341 \text{ hp}} = 75.45 \text{ kW}$$

C-9.3 Calculate Predicted Power at Specified Conditions

C-9.3.1 Gas Power Ratio. Calculate the gas power ratio of specified isentropic power to test isentropic power for reference.

$$r_s = \frac{P_{s,sp}}{P_{s,t}} = \frac{69.84}{75.45} = 0.926$$

C-9.3.2 Predicted Power. Calculate the predicted power for field operation at specified conditions in the tested configuration.

$$P_{pr} = P_t \cdot \frac{P_{s,sp}}{P_{s,t}} = 120.3\,\text{kW} \cdot \frac{69.84}{75.45} = 111.36\,\text{kW}$$

C-9.3.3 Specified Adjustment(s). Correct the predicted power at specified conditions for additional components not included in the test per specification and agreement. The predicted power consumption shall be adjusted to include specified transformer losses. This is the predicted total system electric power consumption at specified design conditions.

$$P_{pr,\text{adj}} = P_{pr} \cdot (1 + 0.02) = 111.36 \cdot 1.02 = 113.6\,\text{kW}$$

C-9.4 Calculation Deviations

Compare the predicted performance at specified conditions to allowable deviations. Compare this to the specified power consumption. The projected power consumption shall be lower than the specified value.

$$\text{Deviation} = \frac{P_{pr,\text{adj}}}{P_{sp}} = \frac{113.6}{118.0} \cdot 100 = 96.3\%$$

C-9.5 Additional Reference Parameters

Calculate additional reference parameters specified but not included in the code. Calculate additional reference information requested by the specifications. Calculate the nominal wire-to-air efficiency, including transformer losses.

$$\eta_{s,pr} = \frac{P_{s,sp}}{P_{pr,\text{adj}}} \cdot 100 = \frac{69.84\,\text{kW}}{113.6\,\text{kW}} \cdot 100 = 61.5\%$$

Calculate the SCFM per kW at specified field conditions.

$$q_{m,\text{per kW}} = \frac{q_{sp,\text{std}}}{P_{pr,\text{adj}}} = \frac{2{,}500\,\text{SCFM}}{109.84\,\text{kW}} = 22.0\,\text{SCFM/kW}$$

NOTE: These reference parameters are not defined in this Code.

C-10 STEP 9: PERFORMANCE DEVIATION REPORTING AND TEST REPORTING

Report data for the test report shall be collated. At a minimum, this shall include

(a) test run number
(b) date of test (day/month/year: 00/00/0000)
(c) start time (hr and min: HH:MM)
(d) finish time (hr and min: HH:MM)
(e) manufacturer model no.
(f) manufacturer serial no.

See Table C-10-1 for the design point values and deviations of this test installation. For this example, the fluctuation of the test parameters during the test was verified within the limits of Table 3-5.5-1. The deviations are within the allowable values from Table 3-5.4-2.

Table C-10-1 Specified and Test Conditions and Deviation

Parameter	Specified Value, Symbol	Test Value, Symbol	Deviation
Ambient Conditions			
Barometric pressure	13.95 psia, $p_{a,sp}$	14.65 psia, $p_{a,t}$	n/a
Inlet static temperature	100°F (559.67°R), T_a	78.2°F (537.87°R), $T_{a,t,\text{static}}$	n/a
Relative humidity	90%, RH_{sp}	47.5%, $\text{RH}_{a,t}$	n/a
Electric Power			
Phase A-B	480 V	483.9 V	100.8
Phase B-C	480 V	481.2 V	100.3
Phase C-A	480 V	482.6 V	100.5
Input line frequency	60 Hz	60.0 Hz	100.0
System power	118 kW, P_{sp}	120.3 kW, P_t	n/a
Flow Rate and Thermodynamic Properties			
Mass flow rate	194.02 lbm/min, $q_{m,sp}$	219.4 lbm/min, $q_{m,t}$	n/a
Discharge static pressure	8.5 psig, $p_{d,sp,ga}$	9.18 psig, $p_{d,t,\text{static},ga}$	n/a
	22.45 psia, $p_{d,sp,\text{static}}$	23.83 psia, $p_{d,t,\text{static}}$	n/a
Inlet static pressure	13.80 psia, $p_{i,sp,\text{static}}$	14.58 psia, $p_{i,t,\text{static}}$	n/a
Pressure ratio	1.626, $r_{p,sp}$	1.6342, $r_{p,t}$	100.5
Equivalent inlet volumetric flow rate	2,980 ft/min, $q_{v,t,sp}$	3,010 ft/min, $q_{v,i,t}$	101.0
Discharge static temperature	n/a	204.1°F (663.77°R), $T_{d,t,\text{static}}$	n/a
Predicted mass flow rate at specified conditions	2,500 SCFM [Note (1)], $q_{sp,\text{std}}$	2,525 SCFM, $q_{pr,\text{std}}$	101.0
Predicted static discharge pressure at specified conditions	8.5 psig, $p_{d,sp,ga}$	8.61 psig, $p_{d,pr,ga}$	101.3259
Total Power [Note (2)]	118 kW, P_{sp}	113.59 kW, $P_{pr,\text{adj}}$	96.3
Additional Parameters/Results Required by Specification Not Included in This Code's Requirements			
Isentropic wire-to-air efficiency at specified conditions	n/a	61.5%, $\eta_{s,pr}$	n/a
SCFM per kW at specified conditions	n/a	22.0 SCFM/kW, $q_{m\ \text{per kW}}$	n/a
Motor speed	n/a	3,550 rpm nameplate, 3,339 rpm at test	n/a
Blower speed	n/a	3,550 rpm min., 7,100 rpm max., 6,678 rpm at test	n/a
Output frequency	n/a	56.4 Hz	n/a
Inlet filter pressure drop at test	n/a	0.07 psi, 1.94 in. H_2O	n/a

NOTES:
(1) SCFM = standard cubic feet per minute specified at standard conditions of 68°F, 14.7 psia, and 36% relative humidity (RH).
(2) Total power includes 2% transformer adjustment.

Nonmandatory Appendix D
Sample Calculation: Machine Reynolds Number Correction

D-1 OBJECT AND SCOPE

The performance of a dynamic blower is affected by the machine Reynolds number (Re_m). Frictional losses in the internal flow passages vary in a manner similar to friction losses in pipes or other flow channels. Differences between the machine Reynolds numbers at test and specified conditions are unlikely within the scope of this code, but the values may be verified by mutual agreement of the parties. If the machine Reynolds number at test operating conditions differs from that at specified operating conditions, a correction to the test results can be used to properly predict the performance of the blower, with agreement between parties.

The flow patterns of dynamic blowers are relatively complex. The term "machine Reynolds number" shall provide a basis for definition in this Code. The machine Reynolds number correction for dynamic blowers recommended in this Appendix is based on Wiesner (1979), simplified for ease of application.

D-2 MACHINE REYNOLDS NUMBER

D-2.1 Reference Points

The machine Reynolds number is used to characterize the state of dynamic viscous fluid forces in a blower at a specific condition. Different machine Reynolds number values may lead to an adjustment of efficiency to account for differing frictional losses occurring within impeller passage ways.

Machine Reynolds number:

$$\mathrm{Re}_m = U_2 \cdot b / \nu \quad \text{(D-2-1)}$$

Reference tip speed for single stage blower:

$$U_2 = \pi N D_2 \quad \text{(L-1-2)}$$

where

b = first stage impeller outlet width (length), expressed in units of feet (ft)
D_2 = impeller outlet blade tip diameter (ft)
N = rotational speed (rpm)
U_2 = velocity of the outer blade tip diameter (ft/sec) (See Nonmandatory Appendix L)
ν = kinematic viscosity of the gas at inlet conditions (ft^2/sec)

Kinematic viscosity

$$\nu = \mu / \rho \quad \text{(D-2-2)}$$

where

ρ = density (lbm/ft^3)
μ = absolute viscosity (lbm/ft·sec)

The machine Reynolds number, Re_m, is a dimensionless quantity; therefore, engineering units for b, μ, ν, ρ, and U_2 should be appropriately and consistently selected to yield the dimensionless quantity.

D-2.2 Correction Factor

Since frictional losses in the dynamic blower are a function of the machine Reynolds number, the correction should be applied to the quantity $(1 - \eta_s)$. The magnitude of the correction is a function of both the machine Reynolds number ratio and the absolute value of the machine Reynolds number, with increasing effect as the machine Reynolds number decreases.

The machine Reynolds number correction that shall be applied is

$$(1-\eta_s)_{pr} = (1-\eta_s)_t \cdot \left(\frac{\mathrm{RA}_{sp}}{\mathrm{RA}_t}\right)\left(\frac{\mathrm{RB}_{sp}}{\mathrm{RB}_t}\right) \tag{D-2-3}$$

$$\mathrm{RA} = 0.066 + 0.934 \cdot \left[\frac{(4.80 \cdot 10^6 \cdot b)}{\mathrm{Re}_m}\right]^{RC} \tag{D-2-4}$$

$$\mathrm{RB} = \frac{\log\left(0.000125 + \frac{13.67}{\mathrm{Re}_m}\right)}{\log\left(\varepsilon + \frac{13.67}{\mathrm{Re}_m}\right)} \tag{D-2-5}$$

$$\mathrm{RC} = \frac{0.988}{\mathrm{Re}_m{}^{0.243}} \tag{D-2-6}$$

where

b = first stage impeller outlet width (length); expressed in units of ft

ε = average surface roughness of the flow passage (in.)

The predicted efficiency at site conditions due to the influence of Reynolds number is

$$\mathrm{Re}_{m_{\mathrm{corr}}} = \frac{\eta_{s,pr}}{\eta_{s,t}} \tag{D-2-7}$$

$$\eta_{s,t} = \frac{T_{i,sp} \cdot \left[\left(\frac{p_{d,sp}}{p_{i,sp}}\right)^{\frac{\kappa_{\mathrm{mix},sp}-1}{\kappa_{\mathrm{mix},sp}}} - 1\right]}{(T_{d,t} - T_{i,t})} \tag{D-2-8}$$

$$\eta_{s,pr} = \left(\eta_{s,t} - 1\right) \cdot \left(\frac{\mathrm{RA}_{sp}}{\mathrm{RA}_t}\right)\left(\frac{\mathrm{RB}_{sp}}{\mathrm{RB}_t}\right) + 1 \tag{D-2-9}$$

Predicted power corrected for Reynolds number:

$$P_{pr} = P_t \cdot \left(\frac{\rho_{sp,i}}{\rho_{t,i}}\right) \cdot \left(\frac{q_{v_{sp}}}{q_{v_t}}\right) \cdot \left(\frac{W_{s_{sp}}}{W_{s_t}}\right) \cdot \left(\frac{\eta_{s,t}}{\eta_{s,pr}}\right) \tag{D-2-10}$$

D-2.3 Limits of Application

Performance variations are a function of the machine Reynolds number as well as of differences between test (Re_{mt}) and specified (Re_{msp}) conditions. Figure D-2.3-1 provides the maximum and minimum permissible ratios for evaluation according to this methodology.

Machine Reynolds Number:

Specified:

$$\mathrm{Re}_{m_{sp}} = U_{2,sp} \cdot b/\nu_{sp} \quad \text{(D-2-11)}$$

Test:

$$\mathrm{Re}_{m_t} = U_{2,t} \cdot b/\nu_t \quad \text{(D-2-12)}$$

Table D-2.3-1 and Figure D-2.3-2 provide the step procedure to account for correcting machine Reynolds number.

Figure D-2.3-1 Allowable Machine Reynolds Number Departures for Dynamic Blowers

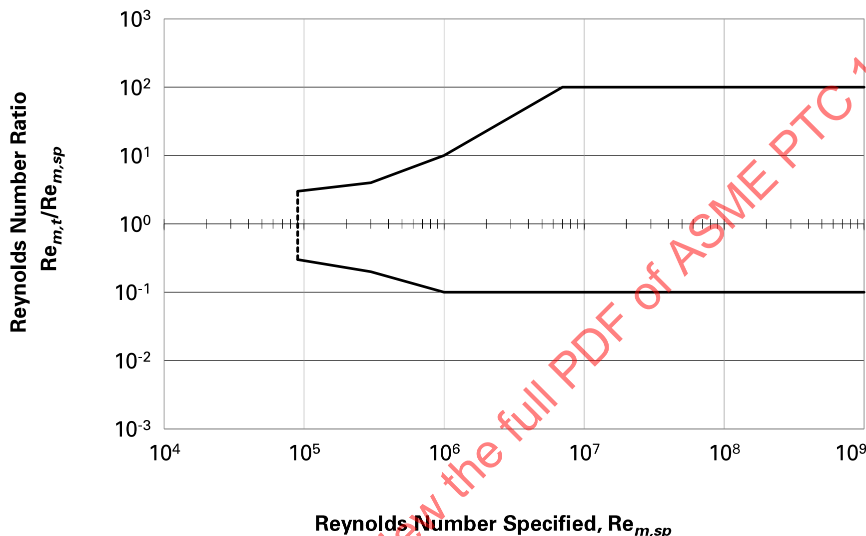


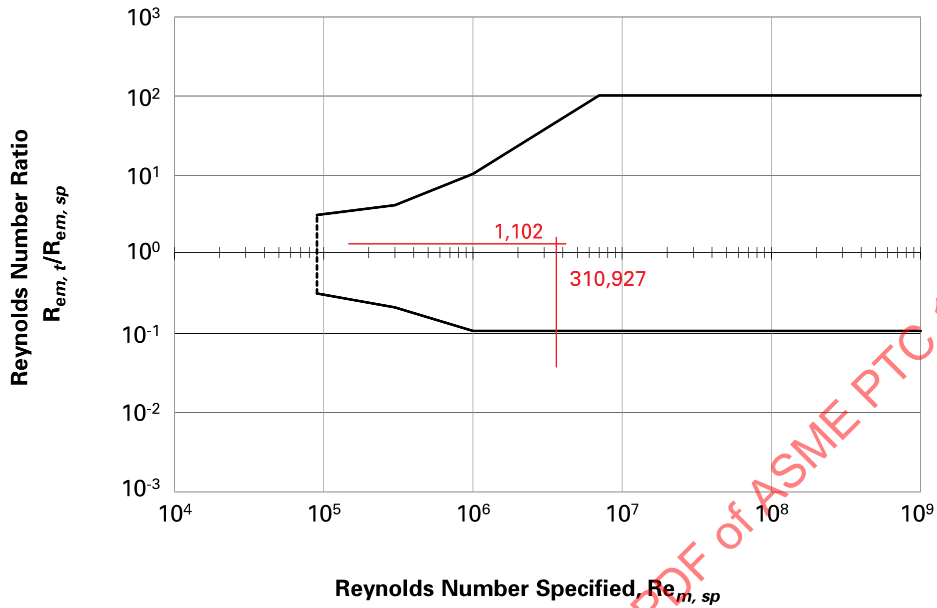
Table D-2.3-1 Machine Reynolds Number Correction Example

Parameter, Symbol	Test	Specified
Rotational speed, N	8,033 rpm	8,000 rpm
Tip speed, U_2	630.91 ft/sec	628.319 ft/sec
Kinematic viscosity, v	1.5623 × 10^{-4}ft^2/sec	1.7143 × 10^{-4}ft^2/sec
Machine Reynolds number, Re_m	342,596 [Note (1)]	310,927 [Note (1)]
Ratio machine Reynolds number, $\left(\frac{\mathrm{Re}_{m_t}}{\mathrm{Re}_{m_{sp}}}\right)$	1.102 [Note (1)]	...
RA calculation	1.11767	1.12534
RB calculation	0.99648	0.99655
RC calculation	0.04465	0.04571
Test isentropic efficiency, $\eta_{s,t}$	84.885%	...
Predicted isentropic efficiency, $\eta_{s,pr}$	...	84.781%
Volumetric flow rate, q_v	4,974 ft^3/min	5,041 ft^3/min
Isentropic head, W_s	12,048 ft·lbf/lb·°R	12,000 ft·lbf/lb·°R
Wire power, P_t	198 hp	...
Inlet density, ρ_i	0.0744 lb/ft^3	0.0692 lb/ft^3
Predicted power, P_{pr}	...	185.87 hp
Predicted power, with machine Reynolds number, $P_{\mathrm{pr},\mathrm{Re}_m}$	...	186.10 hp

GENERAL NOTE: Reference values are as follows: b= 0.95 in. = 0.07917 ft; ε= 0.00012 ft.

NOTE: (1) See Figure D-2.3-2.

Figure D-2.3-2 Reynolds Boundary Limit Verification



D-3 REFERENCE

Wiesner, F. J. 1979. "A New Appraisal of Reynolds Number Effects on Centrifugal Compressor Performance," ASME Journal of Engineering for Gas Turbines and Power, 101 (3): 384–392.

Nonmandatory Appendix E
Sample Calculation: Orifice Flowmeter

E-1 OBJECT AND SCOPE

This Appendix shall provide a sample calculation of flow rate through an orifice metering section that is not calibrated in a hydraulic laboratory. See Table E-1-1 for details of this example. Table E-1-2 presents the air property analysis for inlet and discharge conditions; the calculations used to develop these properties are from Appendix C.

Refer to ASME PTC 19.5-2004, Section 4 for additional information and details of the basis of this calculation. U.S. engineering units shall be used in this example.

E-2 CALCULATING ORIFICE FLOW RATE

E-2.1 Pipe and Orifice Dimensions

Calculate the change in pipe and orifice dimensions due to differential thermal expansion.

$$d_{act} = d_{meas} + \alpha_{SS} \cdot d_{meas} \cdot (T_d - T_{meas})$$

$$d_{act} = 6.128 + 9.0 \cdot 10^{-6} \cdot 6.128 \cdot (204.1 - 68.3) = 6.135 \text{ in.}$$

$$D_{act} = D_{meas} + \alpha_{CS} \cdot D_{meas} \cdot (T_d - T_{meas})$$

$$D_{act} = 10.029 + 6.0 \cdot 10^{-6} \cdot 10.029 \cdot (204.1 - 68.3) = 10.037 \text{ in.}$$

NOTE: If the pipe and orifice material are identical, or if the air temperature is close to the measurement temperature, the above corrections shall not be necessary.

E-2.2 Diameter Ratios

Calculate the ratio of orifice diameter to pipe diameter. Note that, per the recommendations of para. 4-5.12.5, the ratio should be between 0.20 and 0.70.

$$\beta_{act} = \frac{d_{act}}{D_{act}} = \frac{6.135}{10.037} = 0.6113$$

E-2.3 Expansion Factor

Calculate the expansion factor for the upstream flow.

$$\varepsilon_u = 1 - \left(0.41 + 0.35 \cdot \beta_{act}{}^4\right) \cdot \frac{\Delta p_{meas}}{\kappa_t \cdot p_d}$$

$$\varepsilon_u = 1 - \left(0.41 + 0.35 \cdot 0.6113^4\right) \cdot \frac{0.853}{1.3945 \cdot 23.83} = 0.9883$$

Table E-1-1 Orifice Geometry and Measurements

Orifice Design and Geometry	
Parameter, Symbol	**Value**
Discharge pipe diameter, D_{meas}	10.029 in.
Orifice diameter, d_{meas}	6.128 in.
Temperature at diameter measurements, T_{meas}	68.3°F = 528°R
Taps	Flange type
Orifice material	316 stainless steel
Orifice coefficient of thermal expansion, α_{ss}	9 x 10^{-6} in./in. · °F
Pipe material	Carbon steel
Pipe coefficient of thermal expansion, α_{cs}	6 x 10^{-6} in./in. · °F
Expected bias component of uncertainty	0.7%
Test Measurements	
Measurements	**Value**
Static pressure at upstream side of orifice plate, p_d	23.83 psia
Static temperature at upstream side of orifice plate, T_d	204.10°F = 663.77°R
Differential pressure, Δp_{meas}	23.63 in. of H_2O = 0.853 psi

Table E-1-2 Properties of Air at Test Conditions

Property, Symbol	Value
Molecular weight of air/water vapor mixture, $MW_{mix,t}$	28.80 lbm/lbmol
Fraction of water vapor, $x_{vp,t}$	0.0155
Density of air at the upstream side of the orifice plate, $\rho_{mix,d,t,static}$	0.0963 lbm/ft^3
Density of inlet air, $\rho_{mix,i,t,static}$	0.0727 lbm/ft^3
Ratio of specific heats at the upstream side of the orifice plate, κ	1.3989

E-2.4 Mass Flow Rate

Calculate the mass flow rate. Note that the orifice coefficient C_d must be assumed and found by iteration. An initial value of 0.6 shall be used.

$$C_{d1} = 0.60$$

Use ASME PTC 19.5-2004, eq. (3-1.1) to establish constants for the units of measure. Refer to ASME PTC 19.5-2004, Table 3-1 for the appropriate values for the units used; in this case, lbm/hr shall be used.

$$g_c = 32.1741 \frac{\text{lbm} \cdot \text{ft}}{\text{lbf} \cdot \text{sec}^2}$$

$$n = 300 \frac{\text{ft}^2}{\text{sec}^2} \cdot \left(\frac{\text{in.}^2 \cdot \text{sec}^2}{\text{ft}^2 \cdot \text{hr}^2} \right)^{\frac{1}{2}}$$

(a) Calculate the first iteration of the flow rate.

$$q_{m1} = n \cdot \frac{\pi}{4} \cdot d_{\text{act}}^2 \cdot C_1 \cdot \varepsilon_u \cdot \sqrt{\frac{2 \cdot \rho_{\text{mix},d,t,\text{static}} \cdot \Delta p_{\text{meas}} \cdot g_c}{1 - \beta^4}}$$

$$q_{m1} = 300 \cdot \frac{\pi}{4} \cdot 6.135^2 \cdot 0.6 \cdot 0.9883 \cdot \sqrt{\frac{2 \cdot 0.0963 \cdot 0.853 \cdot 32.1741}{1 - 0.6113^4}}$$

$$q_{m1} = 1.3035 \cdot 10^4 \frac{\text{lbm}}{\text{hr}}$$

$$q_{m1} = \frac{1.3035 \cdot 10^4}{60 \frac{\text{min}}{\text{hr}}} \frac{\text{lbm}}{\text{hr}} = 217.3 \frac{\text{lbm}}{\text{min}}$$

E-2.5 Absolute Viscosity

Calculate the absolute viscosity of the air using the formulas in subsection 5-2.

$$\mu_{da} = \left[-9.5472 \cdot 10^{-7}(\text{T}[°\text{R}])^2 + 0.0063768(\text{T}[°\text{R}]) + 0.6702\right] \cdot 10^{-7}\left(\frac{\text{lbf} \cdot \text{sec}}{\text{ft}^2}\right)$$

$$\mu_{da} = \left(-9.5472 \cdot 10^{-7} \cdot 663.77^2 + 0.0063768 \cdot 663.77 + 0.6702\right) \cdot 10^{-7}\left(\frac{\text{lbf} \cdot \text{sec}}{\text{ft}^2}\right)$$

$$\mu_{da} = 4.48 \cdot 10^{-7} \frac{\text{lbf} \cdot \text{sec}}{\text{ft}^2}$$

$$\mu_{vp} = \left[1.0129 \cdot 10^{-6}(\text{T}[°\text{R}])^2 + 0.0028789(\text{T}[°\text{R}]) + 0.08873\right] \cdot 10^{-7}\left(\frac{\text{lbf} \cdot \text{sec}}{\text{ft}^2}\right)$$

$$\mu_{vp} = \left(1.0129 \cdot 10^{-6} \cdot 663.77^2 + 0.0028789 \cdot 663.77 + 0.08873\right) \cdot 10^{-7}\left(\frac{\text{lbf} \cdot \text{sec}}{\text{ft}^2}\right)$$

$$\mu_{vp} = 2.45 \cdot 10^{-7} \frac{\text{lbf} \cdot \text{sec}}{\text{ft}^2}$$

$$\mu_{\text{mix}} = \frac{\mu_{da}\left(1 - x_{vp,t}\right)\sqrt{\text{MW}_\text{a}} + \mu_{vp}(x_{vp,t})\sqrt{\text{MW}_{vp}}}{\left(1 - x_{vp,t}\right)\sqrt{\text{MW}_\text{a}} + (x_{vp,t})\sqrt{\text{MW}_{vp}}}$$

$$\mu_{\text{mix}} = \frac{4.48 \cdot 10^{-7} \cdot (1 - 0.0157)\sqrt{28.97} + 2.45 \cdot 10^{-7} \cdot 0.0157\sqrt{18.015}}{(1 - 0.0157)\sqrt{28.97} + 0.0157\sqrt{18.015}}$$

$$\mu_{\text{mix}} = 4.46 \cdot 10^{-7} \frac{\text{lbf} \cdot \text{sec}}{\text{ft}^2}$$

$$\mu_{\text{mix}} = 4.46 \cdot 10^{-7} \frac{\text{lbf} \cdot \text{sec}}{\text{ft}^2} \cdot 32.17 \frac{\text{lbm} \cdot \text{ft}}{\text{lbf} \cdot \text{sec}^2} = 1.43 \cdot 10^{-5} \frac{\text{lbm}}{\text{ft} \cdot \text{sec}}$$

E-2.6 Pipe Area and Velocity

Calculate the area of the pipe and the velocity of the air in the pipe.

$$A_{\text{pipe}} = \frac{\pi \cdot D_{\text{act}}{}^2}{4} = \frac{\left(\frac{10.037}{12}\right)^2 \cdot \pi}{4} = 0.5495\ \text{ft}^2$$

$$V_1 = \frac{q_{m1}}{\rho_{\text{mix},d,t,\text{static}} \cdot A_{\text{act}}} = \frac{217.3}{0.0963 \cdot 0.5495} = 4{,}106 \frac{\text{ft}}{\text{min}}$$

E-2.7 Reynolds Number

Calculate the Reynolds number.

$$R_{e1} = \frac{\rho_{mix,d,t,static} \cdot D_{act} \cdot V_1}{\mu_{mix}} = \frac{0.0963 \cdot \frac{10.037}{12} \cdot \frac{4{,}106}{60}}{1.43 \cdot 10^{-5}}$$

$$R_{e1} = 3.84 \cdot 10^5$$

E-2.8 Orifice Coefficient

(a) Calculate a new orifice coefficient for the second iteration. See ASME PTC 19.5-2004, eq. (4-8.4).

$$C_{d2} = 0.5959 + 0.312 \cdot \beta_{act}{}^{2.1} - 0.1840 \cdot \beta_{act}{}^{8} + \frac{0.0900 \cdot \beta_{act}{}^{4}}{D_{act} \cdot \left(1 - \beta_{act}{}^{4}\right)} - \frac{0.0337 \cdot \beta_{act}{}^{3}}{D_{act}} + \frac{91.71 \cdot \beta_{act}{}^{2.5}}{R_{e1}{}^{0.75}}$$

$$C_{d2} = 0.5959 + 0.0312 \cdot 0.6113^{2.1} - 0.184 \cdot 0.6113^{8} + \frac{0.09 \cdot 0.6113^{4}}{10.037 \cdot \left(1 - 0.6113^{4}\right)} - \frac{0.0337 \cdot 0.6113^{3}}{10.037} + \frac{91.71 \cdot 0.6113^{2.5}}{\left(3.84 \cdot 10^{5}\right)^{0.75}}$$

$$C_{d2} = 0.6058$$

(b) Calculate the difference between the first estimate and the second value of the coefficient.

$$\frac{C_{d1} - C_{d2}}{C_{d1}} \cdot 100 = 0.97\%$$

Per ASME PTC 19.5-2004, para. 3-14(f), the difference must be less than 2% of the required uncertainty.

$$2\% \cdot 0.7\% = 0.014\%$$

$$0.97\% > 0.014\%$$

E-2.9 Second Iteration

(a) Calculate the second iteration of the mass flow rate.

$$q_{m2} = 300 \cdot \frac{\pi}{4} \cdot 6.135^2 \cdot 0.6058 \cdot 0.9882 \cdot \sqrt{\frac{2 \cdot 0.0963 \cdot 0.853 \cdot 32.1741}{1 - 0.6113^4}}$$

$$q_{m2} = 1.316 \cdot 10^4 \frac{\text{lbm}}{\text{hr}}$$

$$q_{m2} = \frac{1.244 \cdot 10^4}{60 \frac{\text{min}}{\text{hr}}} \frac{\text{lbm}}{\text{hr}} = 219.4 \frac{\text{lbm}}{\text{min}}$$

(b) Calculate the second iteration of the air velocity.

$$V_2 = \frac{219.4}{0.0963 \cdot 0.5495} = 4{,}146 \frac{\text{ft}}{\text{min}}$$

(c) Calculate the second iteration of the Reynolds number.

$$R_{e2} = \frac{0.0963 \cdot \frac{10.037}{12} \cdot \frac{4{,}146}{60}}{1.43 \cdot 10^{-5}} = 3.88 \cdot 10^5$$

(d) Calculate the new orifice coefficient.

$$C_{d3} = 0.5959 + 0.0312 \cdot 0.6113^{2.1} - 0.184 \cdot 0.6113^{8} + \frac{0.09 \cdot 0.6113^{4}}{10.037 \cdot \left(1 - 0.6113^{4}\right)} - \frac{0.0337 \cdot 0.6113^{3}}{10.037} + \frac{91.71 \cdot 0.6113^{2.5}}{\left(3.88 \cdot 10^{5}\right)^{0.75}}$$

$$C_{d3} = 0.6058$$

$$\frac{C_{d2} - C_{d3}}{C_{d2}} \cdot 100 = 0.00\%$$

The difference between the second and third coefficients is 0%, indicating sufficient convergence has occurred.

E-2.10 Mass Flow Rate

Identify the final value of the mass flow rate.

$$q_m = q_{m2} = 219.4 \frac{\text{lbm}}{\text{min}}$$

Calculate the volumetric flow rate of the blower system at inlet and discharge conditions for reference only.

$$q_{v,i} = \frac{q_m}{\rho_{\text{mix},i,t,\text{static}}} = \frac{219.4}{0.0727} = 3{,}018 \frac{\text{ft}^3}{\text{min}}$$

$$q_{v,d} = \frac{q_m}{\rho_{\text{mix},d,t,\text{static}}} = \frac{219.4}{0.0963} = 2{,}278 \frac{\text{ft}^3}{\text{min}}$$

E-3 DISCUSSION

As seen from ASME PTC 19.5-2004, eq. (3-15.11), at large enough Reynolds numbers the discharge coefficient is a very weak function of Reynolds number, which is why so few iterations are required for convergence. If enough about the measured process is known, then the alternative iterative process described in ASME PTC 19.5-2004, para. 3-14(g) can be used. Instead of initially guessing the discharge coefficient, the initial guess would be the flow. With digital computational techniques, it is not critical which method is selected.

In some test systems, the temperature is measured on the downstream side of the orifice. The temperature at the upstream side of the orifice usually can be assumed to be equal to the temperature at the downstream side without significant loss of accuracy.

Nonmandatory Appendix F
Duty Cycles

F-1 INTRODUCTION

This Code describes a method for testing and determining the performance of a blower at specific operating points. The methodology in this Appendix allows determination of field performance and energy consumption if test conditions deviate from specified field conditions.

A blower performance specification typically includes at least one design point identifying blower system flow rate and discharge pressure at identified system ambient or inlet gas conditions [e.g., specified temperature(s), humidity(ies), or pressure(s)]. The specifier typically chooses this design point as the operating point under the anticipated worst case of these parameters during blower system operation.

In most applications, the blower will operate across a range of conditions. The specifier may require testing at selected points in the operating range to verify that the blower system's capabilities and power consumption are consistent with expectations and with the basis for equipment selection.

The operating range and the time of operation at various points in that range will vary with the process and the end use (or uses) of the air delivered by the blower system. The number of evaluation points, the identification of the inlet gas conditions and performance requirement at each evaluation point, and cost or other penalties associated with failure of the system to meet specified requirements shall be based on the judgment of the specifier. They are not integral to the Performance Test Code. It is the intent of this Appendix to provide examples of points for evaluation as well as considerations for use in selecting evaluation points.

F-2 SPECIFIED POINTS OF OPERATION

"Flow rate" shall be the delivered mass flow or, alternatively, the inlet volumetric flow rate as required by the specifications. The flow rate shall consider only the air delivered by the blower system at the discharge from the system and delivered to the process. Multiple points should be specified to represent alternate operating conditions, or as part of a time-weighted life-cycle performance evaluation.

If data at more than one point of operation are required, a test shall be made for each point. The parties to the test shall agree prior to the tests on the method of varying the system resistance by means of discharge restrictions, and on the method of controlling blower airflow rate to obtain the various points of operation.

Each test point shall identify specific system inlet conditions of air mixture and properties. Inlet gas properties shall be identified at the boundary of the blower system and shall include temperature, absolute pressure, and relative humidity. After completion of the test, the principal quantities for each test point shall be corrected as required using the appropriate method identified in this Code for the blower system and as agreed to by the parties.

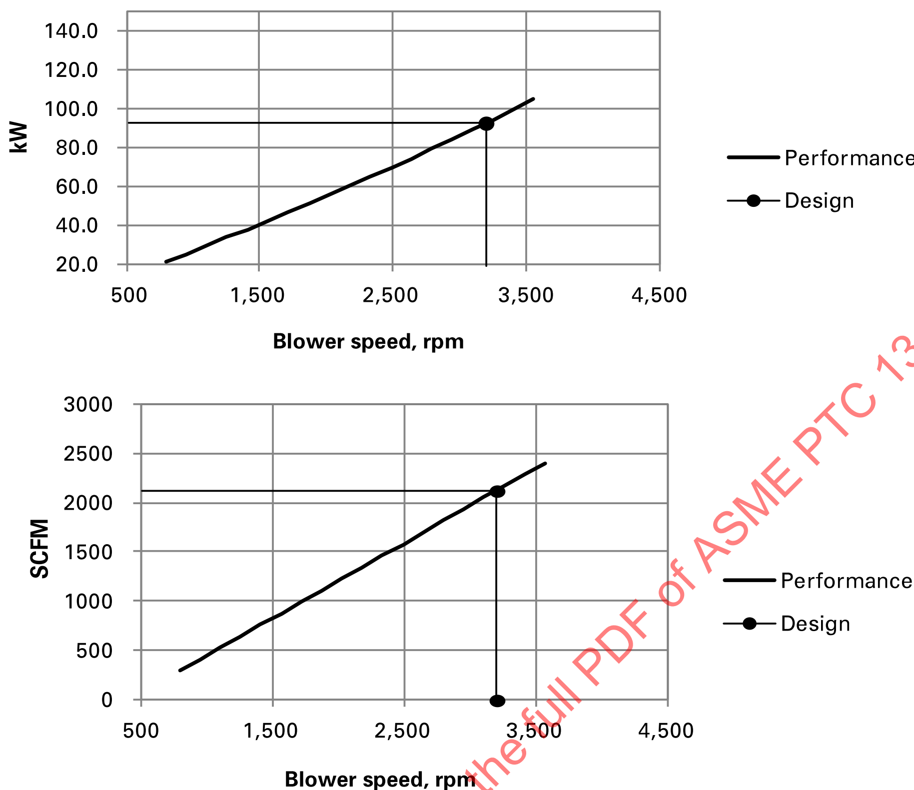
F-2.1 Performance Curve

When performance curves are required to verify the complete range of blower operation, a multipoint test shall be performed. Sufficient data points shall be used to verify the upper and lower limits of operation and to determine the degree of linearity or nonlinearity in the performance curves. Blower performance curves may be based on a constant blower system control setting and variable discharge pressure, or the performance curves may be based on variable blower control settings and a constant discharge pressure. If performance curves are desired, then the parties to the test shall agree beforehand to the number and location of points required to construct the curves.

Performance curves can be used to project energy consumption at alternate operating points. There are many possible formats for performance curves. The format of the curves should be agreed on between the parties prior to the beginning of testing. Performance curves shall be based on a specific set of inlet conditions that should be identified clearly on the curve. The performance data should not be used at other inlet conditions without the appropriate translations.

F-2.1.1 Performance Curve for PD Blowers. See Figure F-2.1.1-1 for a common format for PD performance curves. A minimum of three test points should be used to complete a curve.

Figure F-2.1.1-1 Performance Curve for a Typical PD Blower



GENERAL NOTE: The curve is based on the performance of a PD blower with a design speed of 3,200 rpm, operating under the following inlet conditions:

fluid = air
k = 1.394
MW = 28.717
p at system discharge = 8.9 psig
p at system inlet p = 14.7 psia
p loss at system inlet = 0.203 psi
RH = 36.00%
T_{in} = 100°F

The parties shall agree beforehand if the performance curves are to be obtained by varying blower system speed control settings or blower system discharge pressure, or if performance curves are to be obtained using both methods. The variable speed vs. flow and power format is typically used for PD blowers to establish performance at various speeds or to determine the required operating speed for specific performance points.

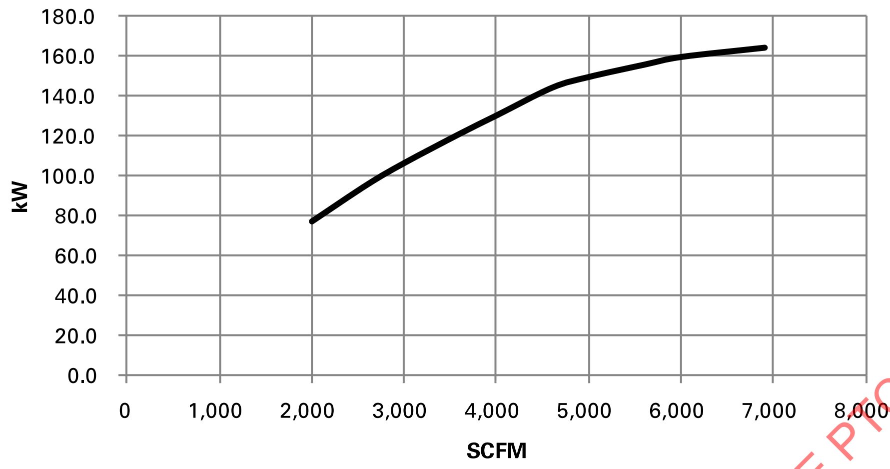
The format in Figure F-2.1.1-1 can be used with dynamic blowers, but this is uncommon. Note that for dynamic blowers, the performance is nonlinear and more than three test points may be needed to accurately define performance.

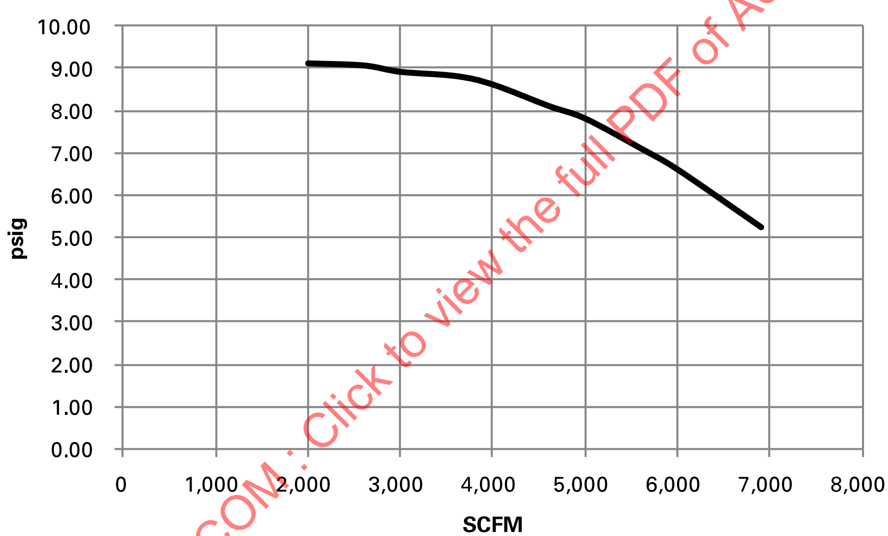
F-2.1.2 Performance Curve for Dynamic Blowers. See Figure F-2.1.2-1 for a dynamic blower performance curve. A minimum of five points should be used to complete a curve. A point shall be taken at approximately the specified design flow rate. The additional points should consist of one point near surge, two points between specified design flow rate and surge, and one point above the specified design flow rate (preferably at 105% or greater of specified maximum flow rate).

The surge and overload test shall be conducted with the speed or other control method at the same setting as that used to obtain the design point. The parties shall agree beforehand if the performance curves are to be obtained by varying blower system control settings, blower system discharge pressure, or if performance curves are to be obtained using both methods.

This format is not appropriate for PD blowers, since at constant speed and variable pressure the performance curve would be essentially a vertical line.

Figure F-2.1.2-1 Performance Curve for a Typical Dynamic Blower

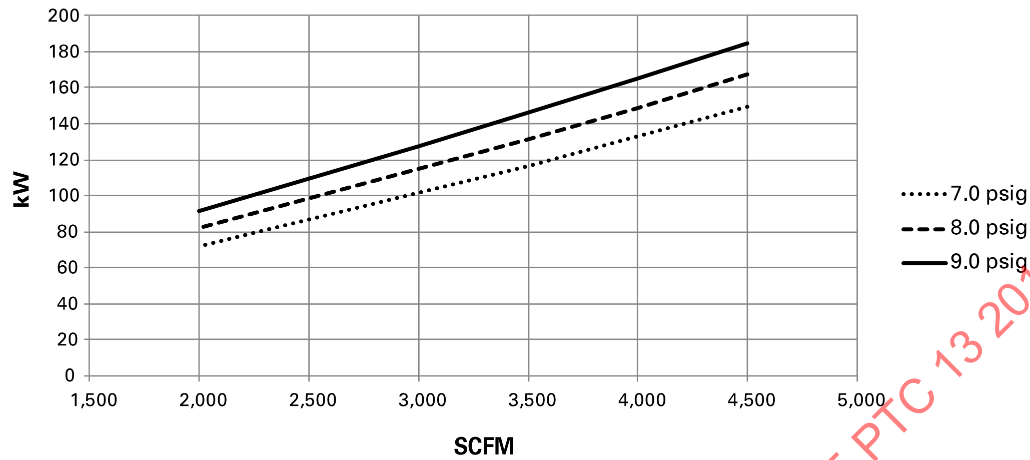




GENERAL NOTE: The curve is based on the performance of a dynamic blower with a design speed of 22,500 rpm, operating under the following inlet conditions:

fluid = air
p at system inlet = 14.12 psia
RH = 75.00%
T = 90°F

Figure F-2.1.3-1 Performance Curve for Any Type Blower



F-2.1.3 Performance Curve for Any Blower. Figure F-2.1.3-1 illustrates a convenient format for showing the energy performance of any type of blower or for comparing blowers: plot power consumption vs. mass flow rate at constant discharge pressure. If multiple pressures are evaluated, power consumption at any point in the operating range should be determined.

This format is also useful for comparing the power consumption of blowers of different designs, as shown in Figure F-2.1.3-2. A minimum of three test points per curve should be used to verify linearity, and more test points may be required for plotting dynamic blower performance.

Figure F-2.1.3-3 demonstrates that superimposing system curve points of pressure vs. flow on this format will show the power demand vs. flow in a variable pressure system.

F-2.2 Economic Considerations

Economic considerations may dictate the number of evaluation points. The cost associated with testing each point shall be balanced against the potential operating cost differential between specified and actual energy consumption. This will influence the number of specified evaluation points. The assessment of penalties based on failure to meet specified power consumption shall be balanced against the potential for higher equipment pricing from suppliers to offset the associated risk. In general, larger blowers and higher energy rates justify more extensive testing and more evaluation points. These factors should be considered in establishing the test requirements.

Figure F-2.1.3-2 Blower Comparison Curve