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# Orifice Mass Flow Calculation in NASA's W-8 Single Stage Axial Compressor Facility

*Richard F. Bozak*  
*Glenn Research Center, Cleveland, Ohio*

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*Richard F. Bozak*  
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National Aeronautics and  
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Glenn Research Center  
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Richard F. Bozak  
National Aeronautics and Space Administration  
Glenn Research Center  
Cleveland, Ohio 44135

## Abstract

Updates to the orifice mass flow calculation for the W-8 Single Stage Axial Compressor Facility at NASA Glenn Research Center are provided to include the effect of humidity and incorporate ISO 5167. A methodology for including the effect of humidity into the inlet orifice mass flow calculation is provided. Orifice mass flow calculations provided by ASME PTC-19.5-2004, ASME MFC-3M-2004, ASME Fluid Meters, and ISO 5167 are compared for W-8's atmospheric inlet orifice plate. Differences in expansion factor and discharge coefficient given by these standards give a variation of about  $\pm 0.75$  percent mass flow except for a few cases. A comparison of the calculations with an inlet static pressure mass flow correlation and a fan exit mass flow integration using test data from a 2017 turbofan rotor test in W-8 show good agreement between the inlet static pressure mass flow correlation, ISO 5167, and ASME Fluid Meters. While W-8's atmospheric inlet orifice plate violates the pipe diameter limit defined by each of the standards, the ISO 5167 is chosen to be the primary orifice mass flow calculation to use in the W-8 facility.

## Introduction

When evaluating the aerodynamic performance of fans and compressors, the accurate measurement of mass flow is critical. Like many other internal flow facilities, the W-8 Single Stage Axial Compressor Facility at NASA Glenn Research Center utilizes an orifice plate for the measurement of mass flow through the facility. The W-8 facility's historical orifice mass flow calculation is based on equations from ASME Fluid Meters 6<sup>th</sup> Ed. (Refs. 1 and 2). Recently, the effect of humidity has been shown to have a significant impact on the evaluation of the performance of a three-stage axial compressor by Berdanier, et al. (Ref. 3). Since W-8 primarily uses an atmospheric inlet, it was decided to update W-8's orifice flow calculations to include the effect of humidity. Along with the orifice mass flow calculation updates to include the effect of humidity, updated equations from ISO (Ref. 4) and ASME (Ref. 5) standards were also included.

This paper will provide an overview of the W-8 Single Stage Axial Compressor Facility's atmospheric inlet orifice plate. The calculation methodology for the inclusion of the effect of humidity and update to ISO 5167 (Ref. 4)/ASME MFC-3M-2004 (Ref. 5) are reviewed. The orifice calculations provided in ISO 5167 and ASME MFC-3M-2004 were found to be the same and are referred to as the ISO 5167 calculations from this point forward. In order to incorporate the effect of humidity REFPROP Version 9.0 (Ref. 6) was utilized for the calculation of thermodynamic properties. Then, the orifice mass flow calculation is compared against other orifice mass flow calculations from ASME PTC-19.5-2004 (Ref. 7), and ASME Fluid Meters (Ref. 2). Finally, the orifice calculations are compared against two other flow calculation methods with an inlet static pressure mass flow correlation (Ref. 1) and an integration fan exit flow from test data obtained during a 2017 turbofan rotor test. All calculations and data shown are in English units as is standard for W-8 testing.

## Nomenclature

$P$	Pressure, psia
$\Delta P$	Differential Pressure, psid
$T$	Temperature, Rankine
$H_{rel}$	Relative Humidity, %
$\rho$	Density, lb <sub>m</sub> /ft <sup>3</sup>
$d$	Orifice Diameter, inches
$D$	Pipe Diameter, inches
$\beta$	Orifice-to-Pipe Diameter Ratio, $d/D$
$l_1$	Distance from Orifice Upstream Face to Upstream Pressure Measurement, inches
$l'_2$	Distance from Orifice Downstream Face to Downstream Pressure Measurement, inches
$L_1$	Normalized Upstream Pressure Measurement Location, $l_1/D$
$L'_2$	Normalized Upstream Pressure Measurement Location, $l'_2/D$
$R_D$	Reynold's Number based on Pipe Diameter ( $D$ )
$\epsilon$	Expansion Factor
$A$	Factor in Calculation of Discharge Coefficient
$M'_2$	Factor in Calculation of Discharge Coefficient
$C$	Discharge Coefficient
$\mu$	Viscosity, lb <sub>m</sub> /ft-s
$\gamma$	Ratio of Specific Heats
$g_c$	Standard Acceleration Due to Gravity, 32.174 ft/s <sup>2</sup>
$R$	Universal Gas Constant, 1545.34896 ft-lb <sub>f</sub> /lb <sub>m</sub> -mol-°R
$M$	Molar Mass, g/mol
$x$	Mole Fraction
$w$	Mass Fraction
$q_i$	Assumed Initial Mass Flow, lb <sub>m</sub> /s
$q_m$	Mass Flow, lb <sub>m</sub> /s

### Subscripts:

1	Upstream Orifice Condition
2	Downstream Orifice Condition
$vs$	Vapor Saturation
$a$	Dry Air Component
$h$	Water Vapor Component

## W-8 Single Stage Axial Compressor Facility

The W-8 Single-Stage Axial Compressor Facility at the NASA Glenn Research Center is an internal flow fan/compressor facility. A schematic of the facility is shown in Figure 1. The facility is capable of delivering up to 7,000 hp at speeds up to 21,240 rpm to a 22-in. diameter fan or compressor. Typically, up to 100 lb<sub>m</sub>/s of air is provided from an atmospheric inlet. Flow conditioning screens in the inlet plenum reduce the turbulence intensity at the fan to less than 1 percent. The flow through the facility is controlled by a sleeve throttle valve. The air can be exhausted through an atmospheric exhaust system or an altitude exhaust system. Facility instrumentation can include up to 400 channels of steady pressure and thermocouple measurement, tip clearance sensing, and up to 96 channels of high speed rotating fan data.

Orifice plates are utilized throughout the facility to measure the mass flow through either an atmospheric or combustion air inlet, as well as the flow through two boundary layer bleed pipes which can be utilized to reduce the inlet boundary layer. While the same calculations can be used on each of the orifice plates, the focus of this paper is on the atmospheric inlet orifice plates.

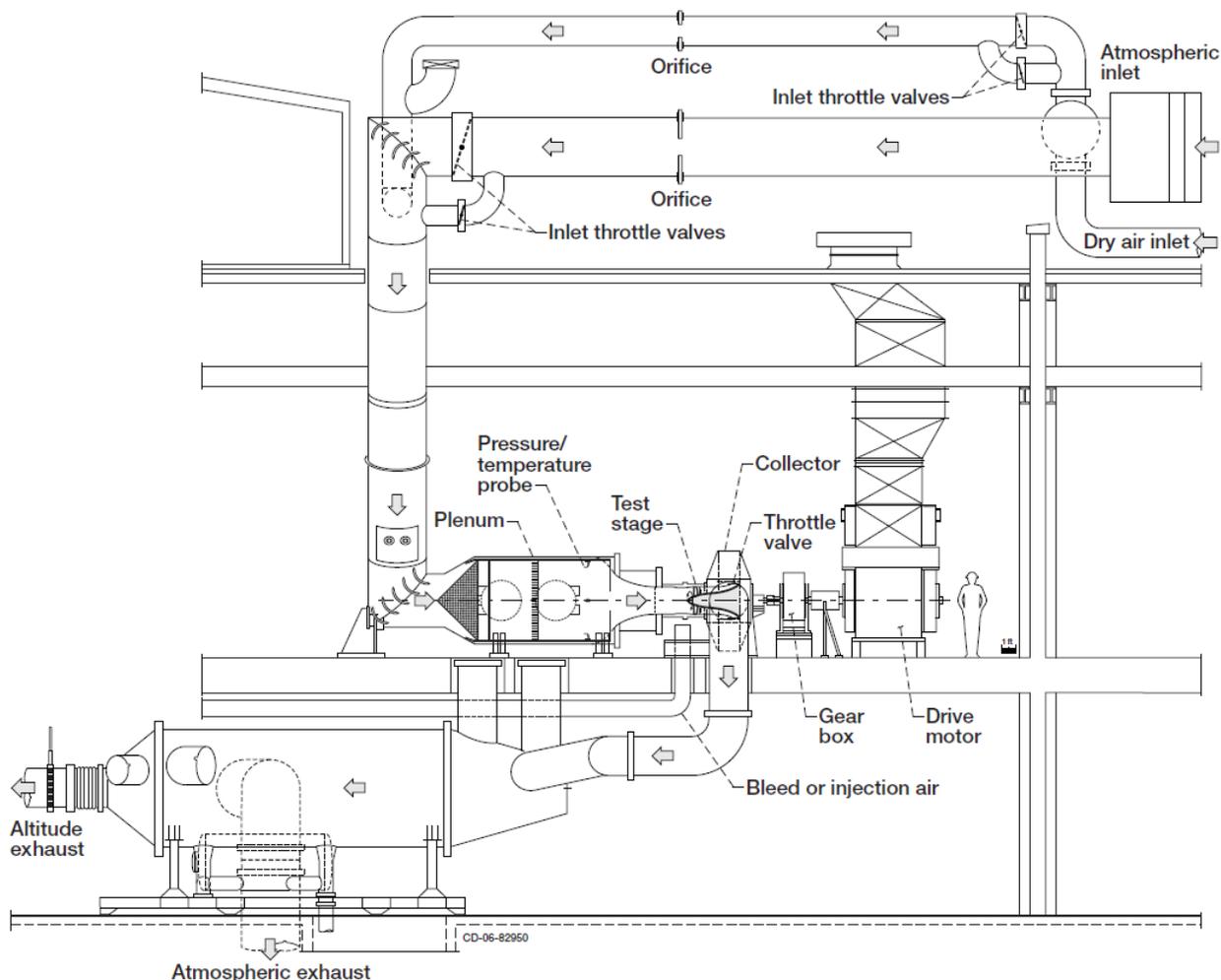


Figure 1.—Schematic of the W-8 Single Stage Axial Compressor Facility at the NASA Glenn Research Center.

## Orifice Mass Flow Calculation

The methodology for including humidity into the ISO 5167 (Ref. 4) orifice flow calculation is shown below. These equations utilize REFPROP (Ref. 6) for the calculation of gas properties. The humidity compensated orifice mass flow calculation is written as a subroutine since it is used to determine the mass flow through either the atmospheric or combustion inlets, as well as the two boundary layer bleed lines.

Pressure, temperature, and relative humidity are measured in the facility's inlet plenum. From these measurements, the partial pressures of air and water vapor are calculated. The partial pressure of water vapor is the relative humidity multiplied by the pressure of vapor saturation for water at the plenum temperature, as shown in Equation (1).

$$P_h = H_{rel} * P_{vs} \quad (1)$$

The partial pressure of dry air is the remaining portion of pressure measured in the plenum.

$$P_a = P - P_h \quad (2)$$

The mole fraction of water vapor can be calculated from the partial pressure of water vapor and the combined pressure. This fraction is assumed to be constant throughout the fluid stream since no other fluids are added or removed.

$$x_h = P_h/P \quad (3)$$

The orifice mass flow subroutine (*wfor*) requires inputs that define the fluid (pressure, temperature, mole fraction of water vapor) and define the orifice geometry (orifice diameter, pipe diameter),

$$wfor(P_1, \Delta P, T_1, x_h, d, D) \quad (4)$$

where,

- $P_1$  Upstream Orifice Pressure, psia
- $\Delta P$  Orifice Differential Pressure, psid
- $T_1$  Upstream Orifice Temperature, °R
- $x_h$  Mole Fraction Water Vapor
- $d$  Orifice Diameter, inches
- $D$  Pipe Diameter, inches

The partial pressures of dry air and water vapor are found from the mole fraction of water vapor ( $x_h$ ) and the upstream orifice pressure ( $P_1$ ),

$$P_{1h} = x_h P_1 \quad (5)$$

$$P_{1a} = (1 - x_h) P_1 \quad (6)$$

These partial pressures and the upstream orifice temperature ( $T_1$ ) are then used to calculate the partial density of each dry air and water vapor. This can be done with REFPROP or the ideal gas law (Eqs. (7) and (8)). The partial densities are added together to obtain a mixed density of the fluid.

$$\rho_{1a} = \frac{P_{1a}}{\frac{R}{M_a} T_1} \quad (7)$$

$$\rho_{1h} = \frac{P_{1h}}{\frac{R}{M_h} T_1} \quad (8)$$

$$\rho_1 = \rho_{1a} + \rho_{1h} \quad (9)$$

The partial densities can then be used to find the mass fractions of dry air or water vapor.

$$w_{1a} = \rho_{1a} / \rho_1 \quad (10)$$

$$w_{1h} = \rho_{1h} / \rho_1 \quad (11)$$

The ratios of specific heats for dry air and water vapor are calculated separately with REFPROP and then combined using a mass weighting.

$$\gamma_1 = w_{1a} * \gamma_{1a} + w_{1h} * \gamma_{1h} \quad (12)$$

The viscosity of the dry air and water vapor mixture is found from a subroutine (*viscmix*( $P_1, T_1, x_h$ )). This subroutine uses REFPROP to find the viscosities of water vapor and dry air at the given pressure and temperature and mixes them based on the formulation by Tsilingiris (Ref. 7). This subroutine is provided for Fortran and MATLAB (The Mathworks, Inc., Natick, MA) in Appendix B.

The orifice diameter is normalized by the pipe diameter for use in the expansion factor and discharge coefficient equations.

$$\beta = d/D \quad (13)$$

The expansion factor ( $\epsilon$ ), is defined in ISO 5167-2 Equation (5).

$$\epsilon = 1 - (0.351 + 0.256\beta^4 + 0.93\beta^8) \left[ 1 - \left( \frac{P_2}{P_1} \right)^{1/\gamma} \right] \quad (14)$$

Since the calculation of Reynolds number requires a mass flow assumption, an iterative calculation is set up to update the assumed mass flow ( $q_i$ ) with the calculated mass flow ( $q_m$ ) until the calculation error has been minimized.

$$R_D = \frac{4q_i}{\pi D \mu} \quad (15)$$

From Reynolds number and geometric parameters, the discharge coefficient is calculated from the empirical equation provided in ISO 5167-2.

$$C = 0.5961 + 0.0261\beta^2 - 0.216\beta^8 + 0.000521 \left( \frac{10^6 \beta}{R_D} \right)^{0.7} + (0.0188 + 0.0063A)\beta^{3.5} \left( \frac{10^6}{R_D} \right)^{0.3} + (0.043 + 0.080e^{-10L_1} - 0.123e^{-7L_1})(1 - 0.11A) \frac{\beta^4}{1 - \beta^4} - 0.031(M'_2 - 0.8M'_2{}^{1.1})\beta^{1.3} \quad (16)$$

where,

$$M'_2 = \frac{2L'_2}{1 - \beta} \quad (17)$$

$$A = \left( \frac{19000\beta}{R_D} \right)^{0.8} \quad (18)$$

For  $D$  and  $D/2$  pressure taps,  $L_1 = l_1/D = 1$  and  $L'_2 = l'_2/D = 0.47$ .

The mass flow is then calculated with the units specified using Equation (1) from ISO 5167-1.

$$q_m = \left(\frac{1}{12}\right) \frac{\pi}{4} d^2 C \epsilon \sqrt{\frac{2\rho_1(\Delta P)g_c}{1-\beta^4}} \quad (19)$$

The residual error is defined as the difference between the calculated mass flow and the assumed mass flow. Each iteration, the assumed mass flow is set equal to the calculated mass flow from the previous iteration.

$$error = q_m - q_i \quad (20)$$

The calculation is considered converged when the residual calculation error is less 0.0001 lb<sub>m</sub>/s. This calculation has been written into a Fortran subroutine for use in W-8's Escort Data System (Appendix A.1.) and into a MATLAB® function (Appendix A.2.).

## Orifice Flow Calculation for the W-8 Atmospheric Inlet

The atmospheric inlet for the W-8 Single Stage Axial Compressor Facility is capable of using orifice plates to measure the mass flow through the facility. The orifice plates are located between the inlet filter housing inlet valves as shown in Figure 1. Upstream and downstream orifice pressures are measured with static pressure taps in four circumferential locations, at axial locations 48-1/8 in. upstream and 23-3/4 in. downstream from the center of the orifice plate. Upstream and downstream orifice fluid temperature is measured in two circumferential locations; 246-7/8 in. from the upstream orifice face and 96-1/8 in. from the downstream orifice face, respectively. The orifice plates are 1/2 in. thick aluminum with the diameters given in Table 1 and the pipe is steel with an inside diameter of 47.5 in.

W-8's atmospheric inlet orifice plates violate the pipe diameter limit of use (~39 in.) defined by all standards evaluated. Also, without flow straighteners, the distance between the orifice plate and downstream elbow is only about 5 pipe diameters which could result in additional uncertainty (as specified in ISO 5167).

The constant inputs to the *wfor* subroutine shown in Equation (4) for W-8's atmospheric inlet are shown below:

- $P_1$  Upstream Orifice Pressure, psia
- $\Delta P$  Orifice Differential Pressure, psid
- $T_1$  Upstream Orifice Temperature, °R
- $x_h$  Mole Fraction Water Vapor
- $d$  Orifice Diameter from Table 1, inches
- $D$  47.5 in.

If we assume standard day inlet pressure and temperature and dry air, the orifice flow measurement capability can be evaluated for the orifice plates available for use in W-8. Figure 2 shows the correlation between orifice differential pressure and mass flow for the W-8 orifice plates shown in Table 1. To avoid Mach number effects, it is specified in ISO 5167-2 (5.3.2.2) to limit measurements to  $P_2/P_1 \geq 0.75$ , which for an atmospheric inlet gives a maximum recommended  $\Delta P$  of about 3.5 psid. The five different orifice plate sizes available cover a wide operating range from about 5 lb<sub>m</sub>/s to over 100 lb<sub>m</sub>/s.

TABLE 1.—W-8 ATMOSPHERIC INLET  
AVAILABLE ORIFICE PLATE SIZES

Available orifice plates		
Orifice plate diameter, <i>d</i> , in.		Orifice-to-pipe diameter ratio, $\beta$
Designated	Actual	
35	34.9950	0.737
30	30.0055	0.632
25	25.0000	0.526
23	23.0038	0.484
19	18.9995	0.400
10	10.0050	0.211

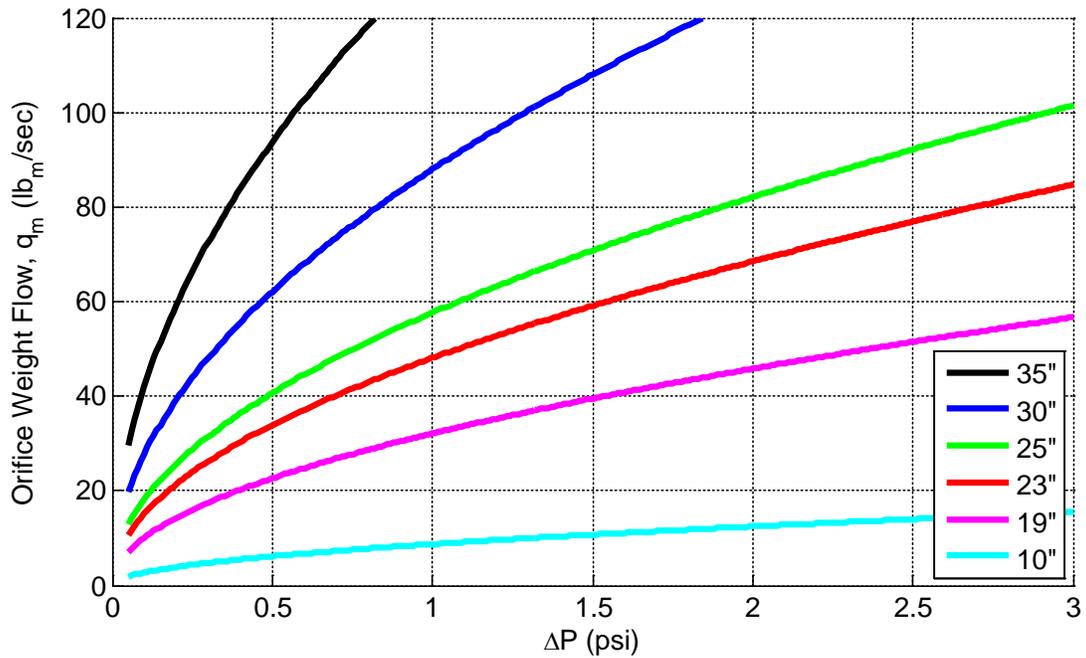


Figure 2.—Flow capability of the W-8 atmospheric inlet orifices with standard day, dry air inlet conditions.

## Comparison With Other Orifice Flow Calculations

The ISO 5167 orifice mass flow calculation is compared with the calculations provided in ASME Fluid Meters 6<sup>th</sup> Ed., which has historically been used to calculate orifice mass flow in W-8, and ASME PTC 19.5. The majority of the calculation is the same, but different equations for the expansion factor ( $\epsilon$ ) and discharge coefficient ( $C$ ) are provided in each. These differences are evaluated for W-8's atmospheric inlet orifice plates.

The expansion factor ( $\epsilon$ ), used in ASME Fluid Meters 6<sup>th</sup> Ed. and ASME PTC 19.5 Equation (3-8.2) is:

$$\epsilon = 1 - (0.41 + 0.35\beta^4) \frac{\Delta P}{\gamma P_1} \quad (21)$$

The difference between expansion factors is shown in Figure 3 for the six W-8 atmospheric inlet orifice plates at standard day inlet conditions. The expansion factor shown in Equation (21) differs from that in Equation (14) (ISO 5167) by up to 0.8 percent for high  $\Delta P$  conditions for all orifice plates except the 35 in. orifice plate.

While the discharge coefficient equation given in ISO 5167 and ASME MFC-3M are identical, two other equations are given in ASME Fluid Meters 6<sup>th</sup> Ed. and ASME PTC 19.5. The discharge coefficient is calculated in ASME Fluid Meters 6<sup>th</sup> Ed. as follows:

$$C = \frac{K}{\sqrt{1-\beta^4}} \quad (22)$$

where,

$$K = K_0 + b\lambda \quad (23)$$

$$K_0 = (0.6014 - 0.1352D^{-0.25}) + (0.3760 + 0.07257D^{-0.25}) \left( \frac{0.00025}{D^2\beta^2 + 0.0025D} + \beta^4 + 1.5\beta^{16} \right) \quad (24)$$

$$b = \left( 0.0002 + \frac{0.0011}{D} \right) + \left( 0.0038 + \frac{0.0004}{D} \right) (\beta^2 + (16.5 + 5D)\beta^{16}) \quad (25)$$

$$\lambda = 1000/R_D \quad (26)$$

The discharge coefficient given in ASME PTC 19.5 Equation (4-8.1) is:

$$C = 0.5959 + 0.0312\beta^{2.1} - 0.1840\beta^8 + \frac{0.0900L_1\beta^4}{1-\beta^4} - 0.0337L_2'\beta^3 + \frac{91.71\beta^{2.5}}{R_D^{0.75}} \quad (27)$$

The discharge coefficients are compared in Figure 4 for the W-8 atmospheric inlet orifice plates with standard day inlet conditions. The ASME PTC 19.5 discharge coefficient varies by up to 3.5 percent from the other calculations for the larger orifice plate diameters (35 and 30 in.). The other discharge coefficients are within about 0.8 percent of each other.

Figure 5 shows the combined effect of the differences in expansion factor and discharge coefficient for standard day inlet conditions for W-8's atmospheric inlet. For the two larger orifice diameters (35 and 30 in.), the ASME PTC 19.5 discharge coefficient difference resulted in a difference between 1 and 3.5 percent. The remaining mass flows for each of the standards are within about  $\pm 0.75$  percent of the ISO 5167 calculation.

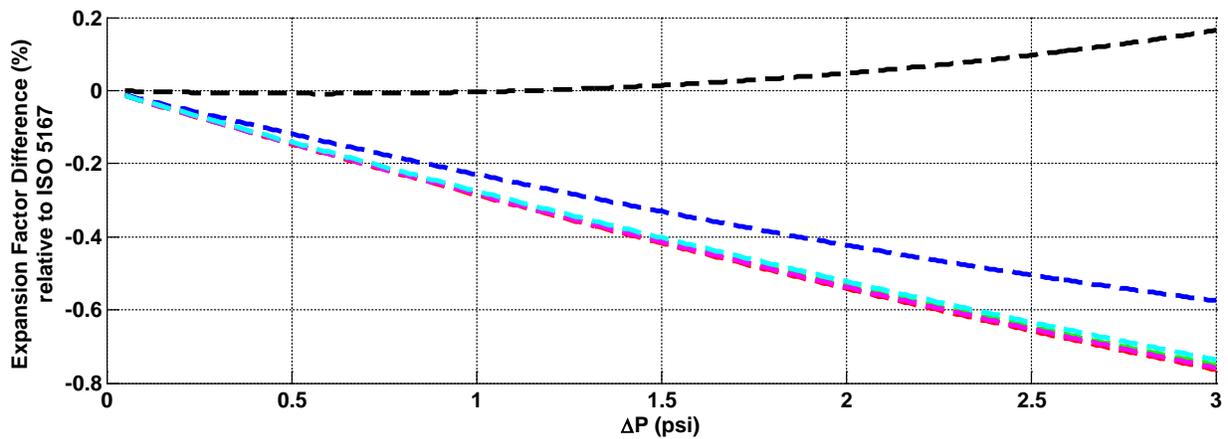
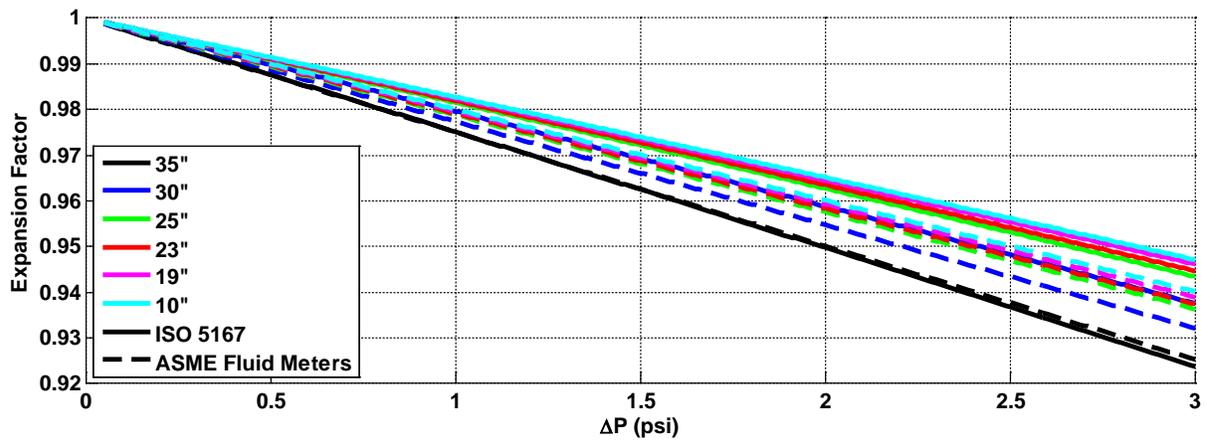


Figure 3.—Comparison of expansion factor between ISO 5167/ASME MFC-3M and ASME Fluid Meters 6<sup>th</sup> Ed./ASME PTC 19.5 for W-8's atmospheric inlet orifice plates.

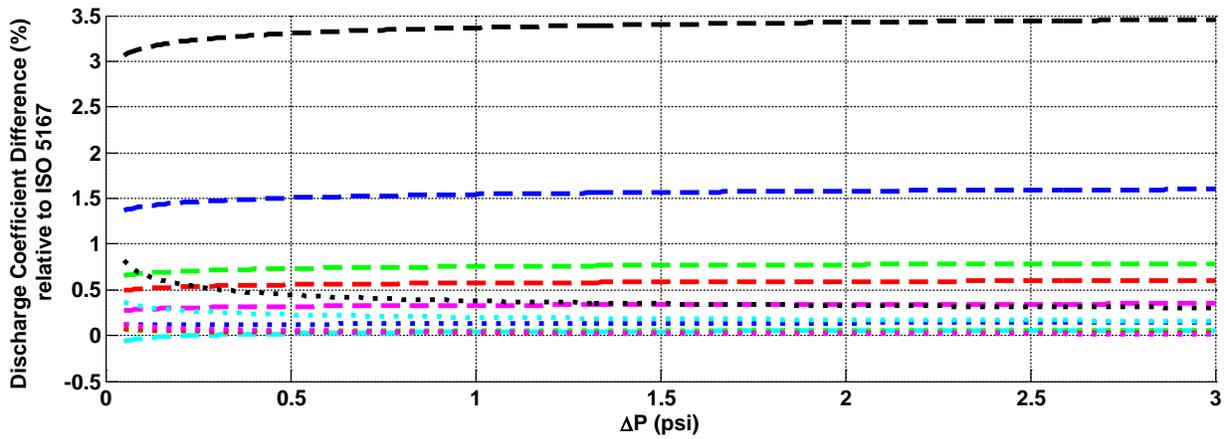
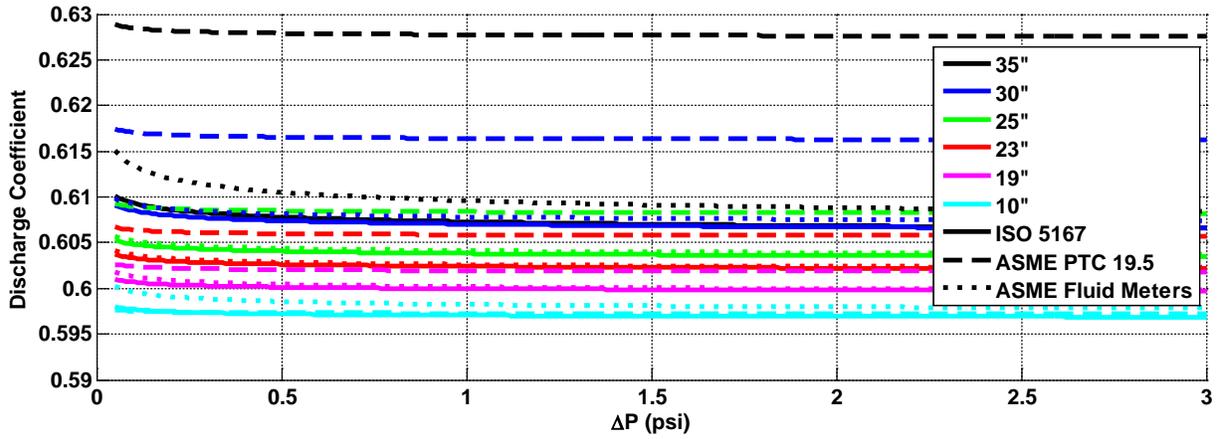


Figure 4.—Comparison of orifice discharge coefficients between ISO 5167/ASME MFC-3M, ASME Fluid Meters 6<sup>th</sup> Ed., and ASME PTC 19.5 for W-8's atmospheric inlet orifice plates.

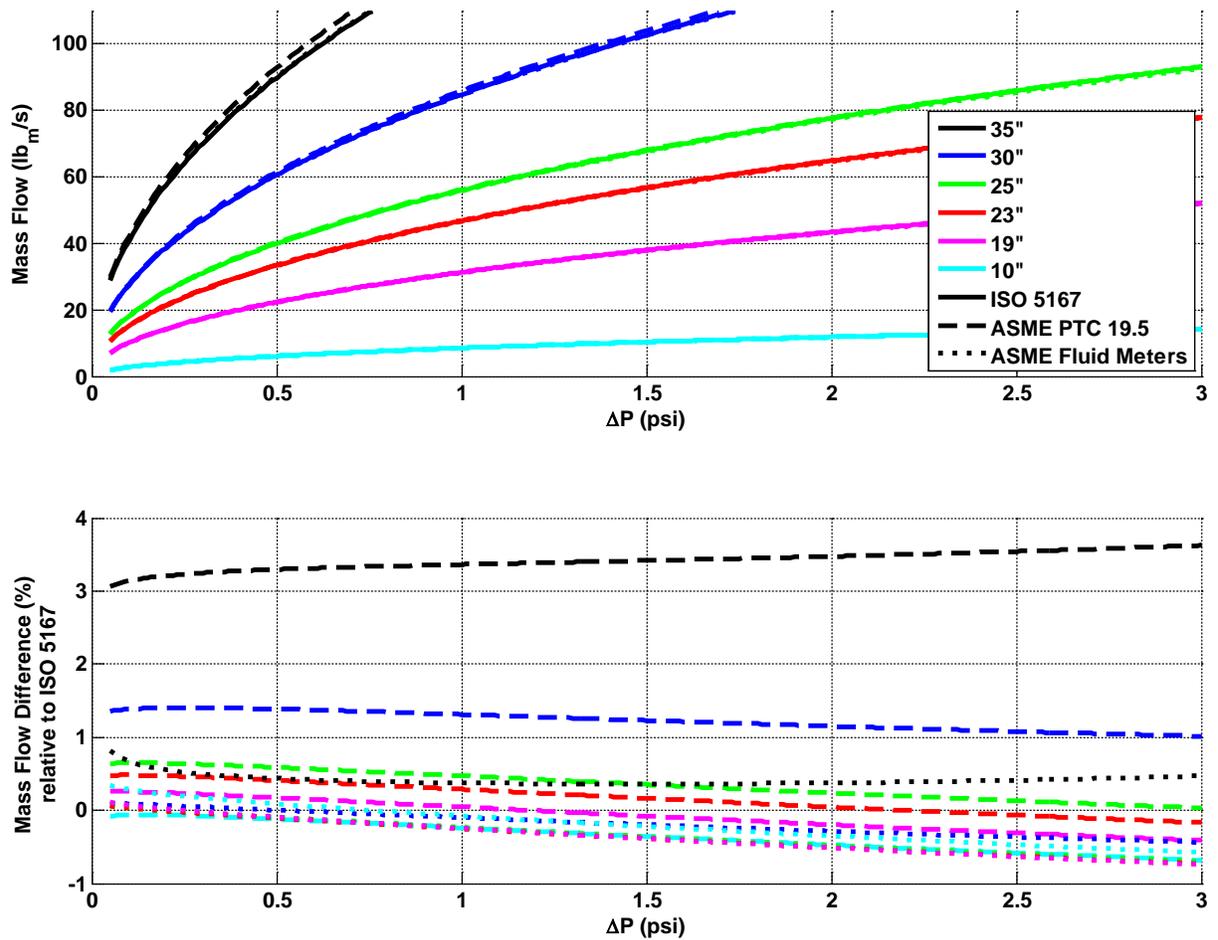


Figure 5.—Comparison of calculated mass flow between ISO 5167/ASME MFC-3M, ASME Fluid Meters 6<sup>th</sup> Ed., and ASME PTC 19.5 for W-8’s atmospheric inlet orifice plates.

## Test Data Comparison

The orifice flow is compared against two other calculation methods. The first being an inlet static pressure correlation described in Appendix A of Reference 1. In this correlation, a ring of static pressures in the inlet are correlated with mass flow using a curve-fit provided by CFD simulations of the W-8 inlet bellmouth. This correlation was shown to be within 0.4 percent of the ASME Fluid Meters 6<sup>th</sup> Ed. orifice flow calculation at the highest flow rate (95 lb<sub>m</sub>/s). The second calculation of mass flow utilizes three seven-element total pressure and temperature rakes behind a rotor and static pressures measured on the end-walls in the same plane. From these measurements, Mach number and density are calculated. Assuming an average flow angle allows for the calculation of axial velocity and mass flow. Due to the constant flow angle assumption and nonuniform flow, this calculation is expected to have the most error.

In February 2017 data was obtained with a 1.5 fan pressure ratio high bypass turbofan rotor installed in the W-8 facility. Data was obtained with the 35 in. orifice plate installed and the mass flow calculations are compared at nine conditions across the operating range in Figure 6. At the time this data was obtained, the downstream pressure taps were installed 30-1/8 in. from the downstream orifice face ( $D/2$ ), which violates the location limits provided in ISO 5167 by about 6 in. This measurement location has since been moved to 23-3/4 in. from the orifice plate, which is within the limits. This change was found to have an impact of about 0.15 percent on the measured mass flow. The orifice calculations are compared relative to the ISO 5167 calculation in terms of percent error. The fan exit mass flow calculation over-predicts the mass flow by up to 5 percent. The ASME PTC 19.5 calculation also over-predicts the mass flow by up to 3 percent. The static pressure mass flow correlation and orifice calculation from ASME Fluid Meters have between 0.5 and 1 percent error relative to the ISO 5167 calculation.

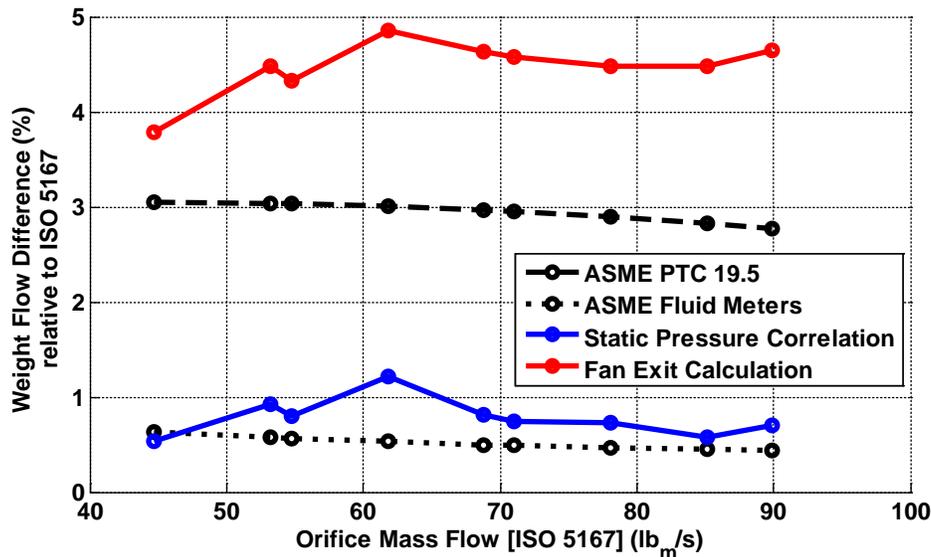


Figure 6.—Comparison of orifice calculations with inlet static pressure correlation and fan exit weight flow calculation relative to the ISO 5167 orifice calculation.

## Conclusions

The W-8 facility's orifice mass flow calculations have been updated to include humidity and follow a standard (ISO 5167). A methodology for including the effect of humidity into the inlet orifice mass flow calculation was provided. Orifice mass flow calculations provided by ASME standards ASME PTC-19.5-2004 and ASME MFC-3M-2004, ASME Fluid Meters, and ISO 5167 were compared for W-8's atmospheric inlet orifice plate. Differences in expansion factor and discharge coefficient give a variation of about  $\pm 0.75$  percent mass flow except for the ASME PTC 19.5 discharge coefficient for the larger orifice diameters (35 and 30 in.) which gave between 1 and 3.5 percent difference. The calculations were also compared with an inlet static pressure mass flow correlation and a fan exit mass flow integration using test data from a 2017 turbofan rotor test in W-8. For this case, the ISO 5167 calculation is within about 0.5 percent of the historic W-8 mass flow calculation (ASME Fluid Meters) and within about 1 percent of the inlet static pressure mass flow correlation. While W-8's atmospheric inlet orifice plate violates the pipe diameter limit of use defined by the standards each of the standards, the ISO 5167 was chosen to be the primary orifice mass flow calculation to use in the W-8 facility.



## Appendix A.—Orifice Mass Flow Subroutines

### A.1. ISO 5167 Orifice Mass Flow FORTRAN/ESCORT Subroutine

```
C-----
C WFOR.FOR
C Subroutine to calculate Orifice Weight Flow (WFO) in lbm/sec.
C Called from FACILITY_CALC.S.TAG.
C
C Modifications:
C 08/16/2017 - Updated routine to follow ISO 5167. Removed
C correction for static tap locations, thermal expansion.
C Assumed Reynold's # diameter changed to D from ORPLATE.
C 08/02/2016 - Updated routine to account for actual upstream and
C downstream tap locations, for thermal expansion, and
C for discharge coefficient based on
C ASME PTC-19.5-2004. (J. Borman and R. Bozak)
C 10/03/2016 - Add convergence error, IERR, to calling sequence.
C (Jerri Vokac for Rick Bozak)
C 09/14/2016 - Initial Version submitted by Rick Bozak and modified
C for Escort system. (Jerri Vokac)
C
C Call: WFOR( UPO, DPOAV, TOAV, XH2O, ORFD, PIPED, WFO, WFORERR )
C
C Inputs:
C UPO: Upstream Orifice Pressure (psia)
C DPOAV: Orifice Delta Pressure (psid)
C TOAV: Orifice Temperature (degR)
C XH2O: Mole Fraction of Water Vapor
C ORFD: Orifice Plate Diameter (inch)
C PIPED: Pipe Diameter (inch)
C
C Output:
C WFO: Orifice Weight Flow (lbm/sec)
C WFORERR: Convergence Error:
C - 0 for successful
C - 1 solution not converged
C-----
C
C SUBROUTINE WFOR( UPO, DPOAV, TOAV, XH2O, ORPLATE, D,
C * WFO, WFORERR )
C-----
C Data Recording Parameters
C-----
COMMON/QAREC/DONT_USE_RDGN,BAROM,IRDTY,IREFB,IABO,IREF,IESP(2),
C * IERLOG,IRCS,IDONT_USE,ISTORCYC,ICYCTY,ICYC,ICCS,
C * IBATCH,NETACT,IAPREC,IAPCLR,IAPRCS,IPRCS,IAPSCAN,
C * NAVGSCAN,ISTDAVG,IREFNSFL,NOREC_CAL,ISGHEAD(5),
C * IDATAVIS,IVIDEOREC,LRNT,IREFNO_MASS,
C * IDRTRANS,ICOMFILE,IREFNO_DUMPS,ISSA
C INTEGER*2 IRDTY,IREFB,IABO,IREF,IESP,IERLOG,IRCS,IDONT_USE,
C * ISTORCYC,ICYCTY,ICYC,ICCS,IBATCH,NETACT,IAPREC,
C * IAPCLR,IAPRCS,IPRCS,IAPSCAN,NAVGSCAN,ISTDAVG,
C * IREFNSFL,NOREC_CAL,ISGHEAD,IDATAVIS,IVIDEOREC,LRNT,
C * IDRTRANS,ICOMFILE
C-----
C Include Standard Constants
C-----
INCLUDE 'CONSTANTS.FOR'
C-----
```

```

C Declare Local Airflow Variables
C-----
      real Md,ko,l,k
      real PHP,PAP,Mu
      real RHOH, RHOH2, RHOA, RHOA2, RHO2, RHOM, WAIR, WH2O
      real GAMH2O, GAMAIR, GAM, XGAM, Y, CD, RED
      real UPO, DPOAV, TOAV, XH2O
      real WFO, MDOT

C-----
C Declare Local Dimensioning Variables
C-----
      real L1, L2, L1ND, L2ND, BETA, D, ORPLATE, PIPED, ORFD
      real ALPHAP, ALPHAO

C-----
C Declare Local REFPROP Variables
C-----
      real*8 wmm, ttrp, tnbpt, tc, pc, Dc, Zc, acf, dip, Rgas
      real*8 p, rho1, rhov, xliq, xvap
      real*8 rhopa, rhoph, rho, eta, tcx, e, h, s, cv, cp, w, hjt
      real*8 x(2)
      real*8 TPROP, PPROP, PPROPA, PPROPH, PPROPA2, PPROPH2, RHOPROP

      parameter (ncmax=20) ! max number of components in mixture
      character hrf*3, herr*255
      character*255 hf(ncmax), hfmix

C REFPROP SETUP initialization (cannot run 1/second)
c      IF ( IBATCH .NE. 0 ) THEN
c          hf(1) = 'AIR.PPF'
c          hf(2) = 'WATER.FLD'
c          hrf = 'DEF'
c          hfmix = 'hmx.bnc'
c          call SETUP( 2, hf, hfmix, hrf, ierr, herr )
c          if (ierr.ne.0) write(*,*) herr
c      ENDIF

      x(1) = 0.5000d0      !! Air composition (molar fractions)
      x(2) = 0.5000d0

C Initialize error term
      ierr = 0

C-----
C REFPROP Inputs
C-----
      PPROP = UPO / KPA2PSI
      TPROP = TOAV / K2R

C Partial Pressure of Water Vapor and Air
      PHP = XH2O * UPO
      PAP = (1 - XH2O) * UPO

      PPROPH = PHP/KPA2PSI
      PPROPA = PAP/KPA2PSI
      PPROPH2 = (XH2O*(UPO-DPOAV))/KPA2PSI
      PPROPA2 = ((1-XH2O)*(UPO-DPOAV))/KPA2PSI

C Air Properties
      CALL PUREFLD(1)
      call info(1, wmm, ttrp, tnbpt, tc, pc, Dc, Zc, acf, dip, Rgas)

```

```

Mair = wmm      !! Molecular Weight, g/mol
Rair = R / Mair  !! Gas Constant for dry air, lbf*ft/lbm*R*mol

call tprho ( TPROP, PPROPA, x, 2, 0, rhopa, ierr, herr)
rhoa = rhopa * Mair * KGM2LBFT      !! Density lb/ft^3

C ADDED 08/02/2017-----
CALL TPRHO ( TPROP, PPROPA2,X, 2, 0, RHOPA, IERR, HERR)
RHOA2= RHOPA * MAIR * KGM2LBFT
C-----

RHOPROP = RHOA/(Mair*KGM2LBFT)
call therm ( TPROP, RHOPROP, x, PPROPA,
* e, h, s, cv, cp, w, hjt)
gamair = cp / cv      !! Ratio of Specific Heats

C Water Vapor Properties
CALL PUREFLD(2)
call info ( 2, wmm, ttrp, tnbpt, tc, pc, Dc, Zc, acf,
*          dip, Rgas)

Mh2o = wmm      !! Molecular Weight, g/mol
Rh2o = R / Mh2o  !! Gas Constant for water vapor,
                !! lbf*ft/lbm*R*mol

call tprho ( TPROP, PPROPH, x, 2, 0, rhoph, ierr, herr)
rhoh = rhoph * Mh2o * KGM2LBFT      !! Density lb/ft^3

C ADDED 08/02/2017-----
CALL TPRHO (TPROP, PPROPH2, X, 2, 0, RHOPH, IERR, HERR)
RHOH2= RHOPH * MH2O * KGM2LBFT
C-----

RHOPROP = RHOH/(MH2O*KGM2LBFT)
call therm ( TPROP, RHOPROP, x, PPROPH,
* e, h, s, cv, cp, w, hjt)
gamh2o = cp / cv      !! Ratio of Specific Heats

C Calculation of Mixture Properties
rhoM = rhoa + rhoh
RHO2 = RHOA2+ RHOH2
wair = rhoa / rhoM
wh2o = rhoh / rhoM

gam = (gamair*wair) + (gamh2o*wh2o)
M = 1 / ((wair/Mair)+(wh2o/Mh2o))
Rm = R/M

C Subroutine to calculate the viscosity of the mixture
call viscmix(UPO,TOAV,XH2O,Mu)

C Calculated Properties
beta = ORPLATE / D      !! Orifice Diameter/ Pipe ID
L1ND = 1                !! Non-dim length from plate to upstream tap
L2ND = 0.47             !! Non-dim length from plate to dwnstm tap

C Assumed Initial Mass Flow
Md = 50.

C Expansion Factor Air (Updated 08/02/2017) [5]
Y=1-((0.351+0.256*(BETA**4)+0.93*(BETA**8))*
* (1-(((UPO-DPOAV)/UPO)**(1/GAM))))

```

```

C Initial Error
  e = 1.
  icount = 0

  do while ( e .gt. 0.0001 )
    icount = icount + 1

C Reynolds Number Air (based on D)
  Red = ( 4. * Md ) / ( pi * ( D / 12. ) * Mu )

C xgam = ( DPOAV / UPO ) / gam

C Discharge Coefficient (Updated 08/02/2017) [4]

  A =(19000*beta/Red)**0.8
  M2 =(2*L2ND)/(1-beta)

  C=0.5961+0.0261*(beta**2)-0.216*(beta**8)
  * +0.000521*(((10**6)*beta/Red)**0.7)
  * +( (0.0188+0.0063*A)*(beta**3.5)*(((10**6)/Red)**0.3))
  * +( (0.043+0.080*exp(-10*L1ND)-0.123*exp(-7*L1ND))
  * *(1-0.11*A)*((beta**4)/(1-(beta**4))))
  * -(0.031*(M2-0.8*(M2**1.1))*(beta**1.3))

C Mass Flow Calculations
  mdot = pi/48.0*(ORPLATE**2)*CD*Y
  * *(2*GC*rhom*DPOAV/(1-beta**4))**0.5

C Calculate Error
  e = abs( mdot - Md )

C Set Mass flow estimate for next iteration
  Md = mdot

  if ( icount .gt. 1000 ) then
    WFORERR = 1
C type *, '***** Orifice Mass Flow Not Converged *****'
    exit
  endif

  enddo

C Set Orifice Mass Flow Output
  wfo = mdot

C-----
  return
  end

```

## A.2. ISO 5167 Orifice Mass Flow MATLAB® Subroutine

```
%% Orifice Weight Flow Calculation
% 8/15/2017: Rick Bozak
%
% Iteratively solves for orifice coefficients and then calculates
% a weight flow for the mixture of dry air and water vapor following
% ISO 5167 and ASME MFC-3M-2004. Uses viscmix subroutine.
% Uses REFPROP for fluid properties.
%
% Requires SETUP of two fluids; (1) 'air.ppf' and (2) 'water.fld'
% For dry air, XH2O = 0.
%
% Usage:
% [WFO IERR] = wfor_iso(P1,DP,T,XH2O,d,D)
%
% Inputs:
% P1: Orifice Upstream Pressure (psia)
% DP: Orifice Delta Pressure (psi)
% T: Orifice Temperature (deg R)
% XH2O: Mole Fraction of Water Vapor
% d: Orifice Diameter (inches)
% D: Pipe Inside Diameter (inches)
%
% Output:
% WFO: Mass Flow of Fluid (lbm/s)
% IERR: Convergence Error, 0 for solved, 1 not converged

%% Test Case
% Inputs
%P1=14.5;      % psia
%DP=0.5;      % psi
%T=534.39;    % R
%XH2O=0.01936; % Mole Fraction of water vapor
%d=35;        % Orifice Diameter, inches
%D=47.5;     % Inside Pipe Diameter, inches

% Output
% WFO = 87.6443; % lbm/sec
%
% 87.64423 = wfor_iso(14.5,0.5,534.39,0.01936,35,47.5)

%% Function
function [wfo C epsilon IERR] = wfor_iso(P1,DP,T1,XH2O,d,D)

IERR=0;

% Unit Conversion Factors
K2R=1.8;
kPa2psi=0.145038;
M2FT=3.280084;
kgm2lbft=0.062428;
pas2lfts=0.671969;

% Air wand Water Vapor Properties
R=1545.34896;      % Universal Gas Constant, lbm-ft/lbf*R
GC=32.1740486;    % Standard Acceleration Due to Gravity

% Pressure and Temperature in SI
PPROP=P1/kPa2psi;
TPROP=T1/K2R;
```

```

% Partial Pressure of Water Vapor
Php=XH20*P1;

% Partial Pressure of Air
Pap=(1-XH20)*P1;

PPROPH=Php/kPa2psi;
PPROPA=Pap/kPa2psi;

% Air
Ma=refpropm('M','T',TPROP,'P',PPROPA,'air.ppf'); % Molecular Weight, g/mol
rhoa=refpropm('D','T',TPROP,'P',PPROPA,'air.ppf')*kgm2lbft; % lbm/ft^3
gama=refpropm('K','T',TPROP,'P',PPROPA,'air.ppf'); % Ratio of specific heats

% Water Vapor
Mh=refpropm('M','T',TPROP,'P',PPROPH,'water'); % Molecular Weight, g/mol
rhoh=refpropm('D','T',TPROP,'P',PPROPH,'water')*kgm2lbft; % lbm/ft^3
gamh=refpropm('K','T',TPROP,'P',PPROPH,'water'); % Ratio of specific heats

% Calculate Mass Fraction of Water Vapor (Specific Humidity)
wa=rhoa./(rhoa+rhoh);
wh=rhoh./(rhoa+rhoh);

% Calculation of Mixture Properties
rho=rhoa+rhoh;
Mu=viscmix(P1,T1,XH20);
gam=(gama*wa)+(gamh*wh);
M=1/((wa/Ma)+(wh/Mh));
Rm=R/M;

% Orifice Plate Properties

% Calculated Properties
beta=d/D; % Orifice Diameter/ Pipe ID
L1=1;
L2=0.47;

% Assumed Initial Mass Flow
qi=50;

% Initial Error
err=1;
count=0;

% Iterative Calculation of Orifice Mass Flow
while (err > 0.0001)
    count=count+1;
    Red=(4*qi)/(pi*(D/12)*Mu); % Reynolds Number (based on d)

    % Expansion Factor [ISO 5]
    epsilon=1-((0.351+0.256*(beta^4)+0.93*(beta^8))*(1-(((P1-DP)/P1)^(1/gam))));

    % Discharge Coefficient [ISO 4]
    A=(19000*beta/Red)^0.8;
    M2=(2*L2)/(1-beta);
    C=0.5961+0.0261*(beta^2)-0.216*(beta^8)...
        +0.000521*((10^6)*beta/Red)^0.7)...
        +((0.0188+0.0063*A)*(beta^3.5)*((10^6)/Red)^0.3)...
        +((0.043+0.080*exp(-10*L1)-0.123*exp(-7*L1))*(1-0.11*A)*((beta^4)/(1-
(beta^4)))))...
        -(0.031*(M2-0.8*(M2^1.1))*(beta^1.3));

```

```

% Mass Flow [2-1]
qm=(1/12)*(pi/4)*(d^2)*C*epsilon*...
    sqrt((2*rho*DP*GC)/(1-(beta^4)));

% Calculate Error
err=abs(qm-Md);

% Break Loop if Mass Flow Does Not Converge
if count>1000
    disp('Orifice Mass Flow Not Converged')
    IERR=1;
    break
end

% Set Mass flow estimate for next iteration
qi=qm;

end

% Set Mass Flow for Output
wfo=qm;

```



## Appendix B.—Viscosity Mixture Subroutine

### B.1. Viscosity Mixture FORTRAN/ESCORT Subroutine

```

C-----
C  VISCMIIX.FOR
C    Subroutine to calculate the viscosity of a mixture of dry air
C    and water vapor.
C    Called from WFOR.FOR.
C
C  Modifications:
C  11/01/2016 - Initial Version
C                ( Rick Bozak)
C
C  Call:  VISCMIIX( P, T, XH2O , Mu)
C
C  Inputs:
C          P:          Pressure (PSIA)
C          T:          Temperature (R)
C          XH2O:       Mole Fration of Water Vapor
C
C  Output:
C          Mu:         Viscosity (lb-ft/s)
C-----
C-----
      SUBROUTINE VISCMIIX( Pdum, T, XH2O, Mu )

      real Mair,Mh2o,PHP,PAP,Mu,PHIAV,PHIVA,Muair,Muh2o
      real*8 wmm, ttrp, tnbpt, tc, pc, Dc, Zc, acf, dip, Rgas
      real*8 p, rho1, rhov, xliq, xvap
      real*8 rho, eta, tcx, e, h, s, cv, cp, w, hjt
      real*8 x(2)

      real*8 TPROP, PPROP, PPROPA, PPROPH, RHOPROP
      real*8 k2r, kpa2psi, m2ft, kgm2lbft, pas2lfts

      character*255 hrf*3, herr*255
      character*255 hfmix

      data pi/3.14159/

C-----
c For REFPROP

      x(1) = 0.5000d0      !! Air composition (molar fractions)
      x(2) = 0.5000d0

C-----

      ierr = 0

C  Temperature Conversion Kelvin to Rankine
      K2R = 1.8

C  Pressure Conversion kPa to psi
      KPA2PSI = 0.145038

C  Length Conversion m to ft

```

```

M2FT = 3.28084

C Density Conversion kg/m^3 to lbm/ft^3
KGM2LBFT = 0.062428

C Viscosity Conversion Pa-s to lbm/ft-s
PAS2LFTS = 0.671969

C Air Wand Water Vapor Properties
R = 1545.33      !! Universal Gas Constant, lbm-ft/lbf*R
GC = 32.174      !! Standard Acceleration Due to Gravity

C REFPROP Inputs
p = pdum                !! jav
PPROP = P / KPA2PSI
TPROP = T / K2R

C Partial Pressure of Water Vapor and Air
PHP = XH2O * P
PAP = (1 - XH2O) * P

PPROPH = PHP/KPA2PSI
PPROPA = PAP/KPA2PSI

C Air Properties
CALL PUREFLD(1)
call info( 1, wmm, ttrp, tnbpt, tc, pc, Dc, Zc, acf, dip, Rgas)
Mair = wmm              !! Molecular Weight, g/mol
Rair = R / Mair         !! Gas Constant for dry air, lbf*ft/lbm*R*mol

call tprho ( TPROP, PPROPA, x, 2, 0, rho, ierr, herr)
rhoa = rho * Mair * KGM2LBFT      !! Density lb/ft^3

RHOPROP = rhoa / (Mair*KGM2LBFT)
call trnprp (TPROP,RHOPROP,x,eta,tcx,ierr,herr)
Muair = eta * 1e-6 * PAS2LFTS

C Water Vapor Properties
CALL PUREFLD(2)
call info ( 2, wmm, ttrp, tnbpt, tc, pc, Dc, Zc, acf,
*          dip, Rgas)

Mh2o = wmm              !! Molecular Weight, g/mol
Rh2o = R / Mh2o         !! Gas Constant for water vapor,
!! lbf*ft/lbm*R*mol

call tprho ( TPROP, PPROPH, x, 2, 0, rho, ierr, herr)
rhoh = rho * Mh2o * KGM2LBFT      !! Density lb/ft^3

RHOPROP = RHOH/(MH2O*KGM2LBFT)
call trnprp (TPROP,RHOPROP,x,eta,tcx,ierr,herr)
Muh2o = eta * 1e-6 * PAS2LFTS

C Mixture Properties
rho = rhoa + rhoh
wair = rhoa / rho
wh2o = rhoh / rho

C Equation 22
PHIAV = ((2**0.5)/4)*((1+(Mair/Mh2o))**-.5)*
&        ((1+((Muair/Muh2o)**0.5)*((Mh2o/Mair)**0.25))**2)

C Equation 23

```

```
PHIVA = ((2**0.5)/4)*((1+(Mh2o/Mair))**-0.5)*  
&      ((1+((Muair/Muh2o)**0.5)*((Mair/Mh2o)**0.25))**2)
```

C Equation 20 to Combine

```
Mu = ((wair*Muair)/(wair+(wh2o*PHIAV)))+  
&     ((wh2o*Muh2o)/(wh2o+(wair*PHIVA)))
```

```
C-----  
    return  
    end
```

## B.2. Viscosity Mixture MATLAB® Subroutine

```
% Function for Calculating the Viscosity of an Air/Water Vapor Mixture
% Rick Bozak: 9/16/2016
%
% Follows Tsilingiris, P.T "Thermophysical and transport properties
% of humid air at temperature range between 0 and 100 C", Energy Conversion
% and Management, Vol. 45, Issue 5, p. 1098-1110, May 2008.
%
%
%% Test Case
% Inputs
%P=14.5;    % psia
%T=534.39; % R
%XH=0.01936; % Mole Fraction
%
% Output
% Mum = 1.2274e-05
% 1.2279e-05 = viscmix(14.5,534.39,0.01936)

function [Mum]=viscmix(P,T,XH)

% Unit Conversion Factors
K2R=1.8;
kPa2psi=0.145038;
M2FT=3.280084;
kgm2lbft=0.062428;
pas2lfts=0.671969;

% Pressure and Temperature in SI
PPROP=P/kPa2psi;
TPROP=T/K2R;

% Partial Pressure of Water Vapor
Php=XH*P;

% Partial Pressure of Air
Pap=(1-XH)*P;

PPROPA=Pap/kPa2psi;
PPROPH=Php/kPa2psi;

% Air
Ma=refpropm('M','T',TPROP,'P',PPROPA,'air.ppf'); % Molecular Weight, g/mol
Mua= refpropm('V','T',TPROP,'P',PPROPA,'air.ppf')*pas2lfts; % Viscosity, lbm/ft-s
rhoa=refpropm('D','T',TPROP,'P',PPROPA,'air.ppf')*kgm2lbft; % lbm/ft^3

% Water Vapor
Mh=refpropm('M','T',TPROP,'P',PPROPH,'water'); % Molecular Weight, g/mol
Muh=refpropm('V','T',TPROP,'P',PPROPH,'water')*pas2lfts; % Viscosity, lbm/ft-s
rhoh=refpropm('D','T',TPROP,'P',PPROPH,'water')*kgm2lbft; % lbm/ft^3

rho=rhoa+rhoh;

% Calculate Mass Fraction of Water Vapor (Specific Humidity)
wa=rhoa./rho;
wh=rhoh./rho;

% Equation 22
phiav=(sqrt(2)/4)*((1+(Ma/Mh))^(1/2))*...
((1+((Mua/Muh)^(1/2))*((Mh/Ma)^(1/4)))^2);
```

```

% Equation 23
phiva=(sqrt(2)/4)*((1+(Mh/Ma))^(1/2))*...
    ((1+((Muh/Mua)^(1/2))*((Ma/Mh)^(1/4)))^2);

% Equation 20, Viscosity of the Mixture
Mumix=((wa*Mua)/(wa+(wh*phiav)))+(wh*Muh)/(wh+(wa*phiva));

Mum=Mumix;

```

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