FLOWMETER CALIBRATION FACILITY FOR
HEATED GAS MIXTURES

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Abstract

The National Institute of Standards and Technology (NIST) has designed and built a new gas calibration facility that permits flowmeter performance testing under conditions of variable flow, temperature, and gas composition. The facility meters pure air, nitrogen, carbon dioxide, and argon with critical flow nozzles that have been calibrated using existing NIST gas flow standards. Water vapor is added in a saturator vessel and the mass flow of water is calculated from a dew point temperature measurement. The metered gas mixture is heated by an electric circulation heater to temperatures between 293 and 700 K. The flow range of the facility is nominally 60 to 6200 liters per minute and the uncertainty of the flow is 1% of reading or less. Testing of flowmeters is underway with temperature and composition conditions which simulate automobile exhaust.

Introduction

The Exhaust Meter Calibration Facility (EMCF) was built to conduct research and performance tests on flow meters with variable gas composition, temperature, and flow. In particular, accurate flow measurements are needed by the auto manufacturers to meet pollution output requirements and to evaluate engine performance. The test conditions

available in the EMCF were established through interaction with the American Industry / Government Emissions Research group, an organization of U. S. auto industry and environmental regulation agencies.

The EMCF generates simulated auto exhaust by summing metered pure gas streams of the major constituents found in real exhaust. The flow range for the simulated exhaust is 60 to 2000 standard liters per minute (slm) (2 to 72 standard cubic feet per minute, scfm); standard conditions are 293.15 K and 101.325 kPa. In an alternate mode of operation, the EMCF can also provide humidified air flows from 85 to 6200 slm (3 to 220 scfm). The gas mixture can be heated to temperatures from 293 to 700 K (68 to 800 F).

This article provides detailed descriptions of the design and the calculation procedures used for the EMCF, and presents an uncertainty analysis for the facility.

Facility Design

The EMCF generates a simulated exhaust flow by mixing flows of pure air, nitrogen, carbon dioxide, and argon that have been metered with critical flow nozzles. Water vapor is added using a saturator vessel and the mass flow of water is calculated from the dew point temperature. Before entering the meter under test, the gas mixture is heated with an electric circulation heater. A schematic diagram of the EMCF is shown in Figure 1 and a detailed explanation of the diagram follows.
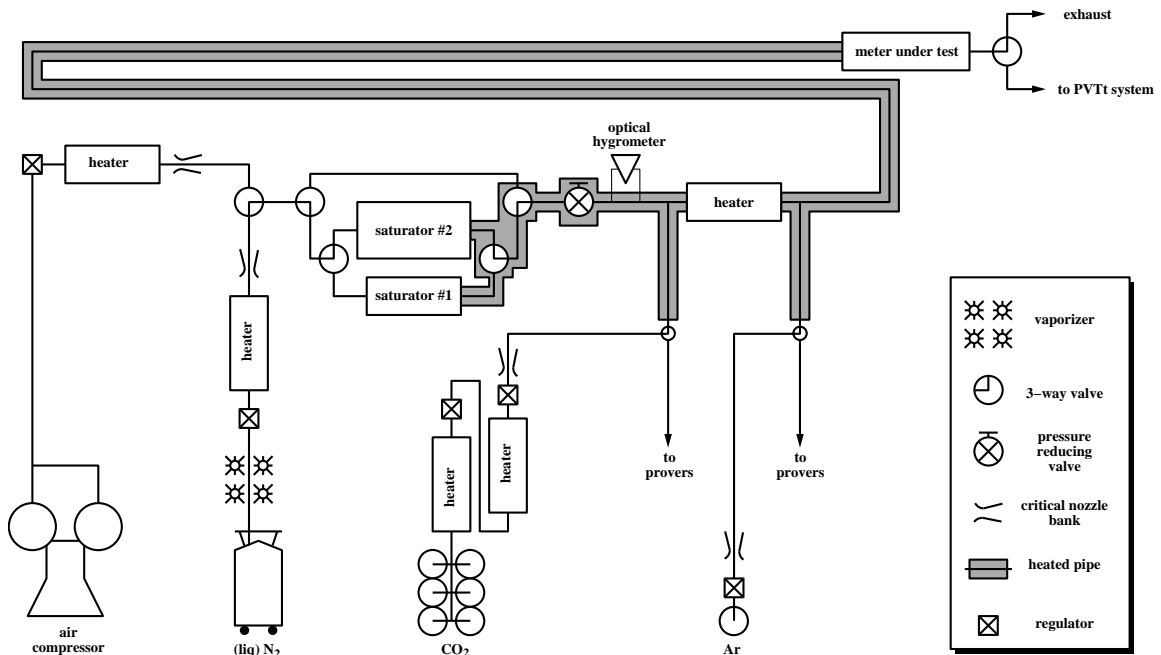

Figure 1. A schematic diagram of the Exhaust Meter Calibration Facility.

Compressed, dry air (dew point temperature < -10 C) flows from the compressor through a 7.5 cm pipe to the EMCF room. The pipe was sized to accommodate possible future expansion of the facility maximum flow to 28,000 slm of air. The pipe steps down to 2.5 cm diameter 316 stainless steel tubing that feeds a dome loaded regulator which controls the pressure upstream of a critical flow nozzle, and thereby controls the flow of air. The flow next enters an electric circulation heater which allows heating of the air so that when it enters the saturator vessel it will be at approximately the dew point temperature that is being sought.

The air flows through a system of three-way valves which select one of four critical flow nozzles from a nozzle bank (see Figure 2). The dimensions and flow range available for all the nozzles in the EMCF are listed in Table 1. Each nozzle is operated over approximately a 3 : 1 flow range so the turn-down ratio for the entire air nozzle bank is 81 : 1. Critical nozzles were selected because of their excellent calibration stability over time and their simple instrumentation requirements: a single temperature and pressure measurement. The pressure at the inlet to the nozzle bank is measured with a 1000 kPa full scale pressure transducer, while the temperature is measured with platinum resistance temperature devices (RTD) installed approximately 6 tube diameters upstream from each nozzle entrance. The nozzles have been calibrated *in situ* (with the gas they meter in the EMCF) using the NIST single species gas flow standards.
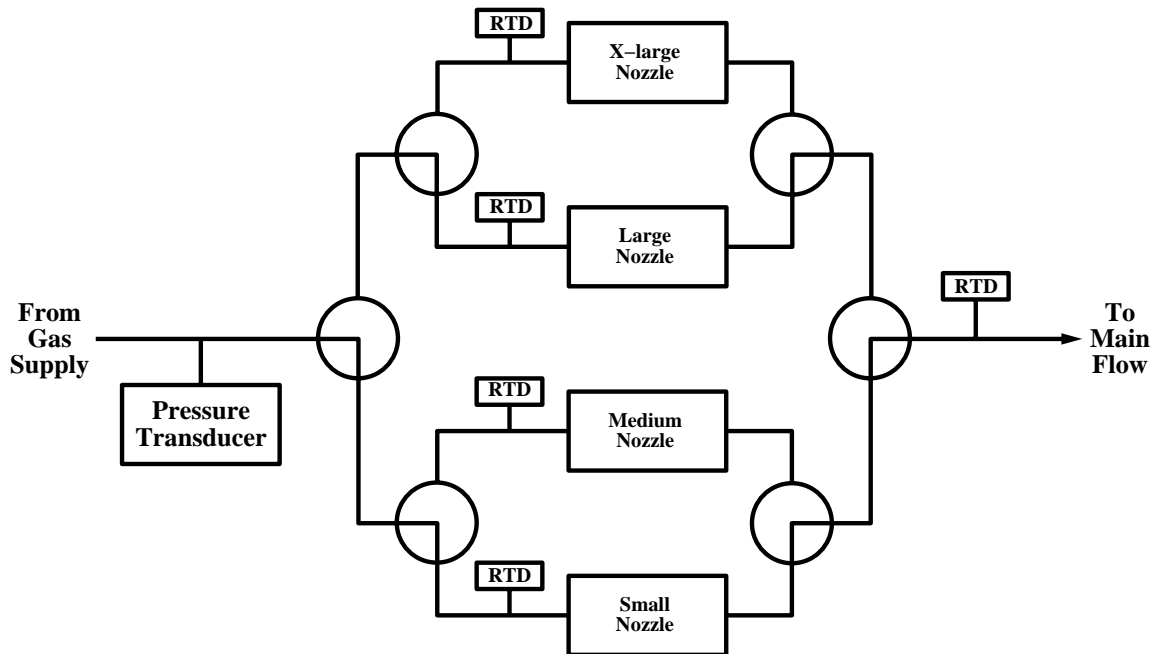

Figure 2. A bank of critical flow nozzles in the EMCF.

A similar nozzle bank and gas supply system is used to meter nitrogen. The source of nitrogen is three 240 liter dewars, and three vaporizer towers connected in parallel. The nitrogen nozzle bank is composed of three nozzles, so the turn-down ratio for nitrogen

flow is 27 : 1. At the intersection of the air and nitrogen gas streams is a three way valve that selects which of the two gases is directed into the saturator system and at this point the tubing steps up to a diameter of 5 cm.

Table 1. Dimensions and flow ranges for the critical nozzles and saturators used in the EMCF.

Gas	Throat Diam. (cm)	Mass Flow Range (g/s)	Volumetric Flow Range (slm)
Argon	0.021	0.022 - 0.065	0.795 - 2.35
Argon	0.035	0.065 - 0.180	2.35 - 6.50
Argon	0.060	0.180 - 0.565	6.50 - 20.4
CO_2	0.093	0.383 - 1.15	12.5 - 37.5
CO_2	0.159	1.15 - 3.30	37.5 - 108
CO_2	0.272	3.30 - 9.00	108 - 323
Nitrogen	0.162	1.14 - 3.6	58.7 - 185
Nitrogen	0.277	3.6 - 10.7	185 - 551
Nitrogen	0.474	10.7 - 31.0	551 - 1597
Air	0.180	1.33 - 4.6	66.3 - 229
Air	0.309	4.6 - 13.6	229 - 678
Air	0.531	13.6 - 39.0	678 - 1944
Air	0.913	39.0 - 105	1944 - 5233
Water	Bypass	0	0
Water	Saturator 1	0.01 - 1.78	0.8 - 135
Water	Saturator 2	1.78 - 12.2	135 - 930

Another set of three way valves selects between a bypass around the saturators (no water vapor added), a small saturator vessel, and a large saturator vessel. The small vessel (30 cm diameter, 122 cm long) is used for lower flows for which the residence time of the gas in the large vessel would be too long. The large vessel (91 cm x 122 cm) is needed to attained the desired water concentrations at the higher gas flows. Each saturator vessel consists of water heaters, spray trees, cooling coils, and controls for the level, flow, and temperature of water (see Figure 3). At the inlet of the vessel, the gas strikes a cone shaped flow diffuser that generates a more uniform velocity profile through the vessel. Heated water is sprayed into the flowing dry gas and evaporates, bringing the gas to near saturation with water vapor. The gas then flows through a cooling coil at the desired dew point temperature, and excess water condenses back to the liquid phase. There is a spray eliminator (a system of baffles) to prevent entrained liquid water from reaching the vessel

exit. An RTD installed at the vessel exit is used to control the spray water heating, and indirectly, the cooling coil temperature. A second RTD is used to form a cascade control loop so that when the gas stream is flowing through the saturator bypass pipe, the water temperature in the saturator vessel is maintained at a user specified temperature. This allows the saturator water to be pre-heated.
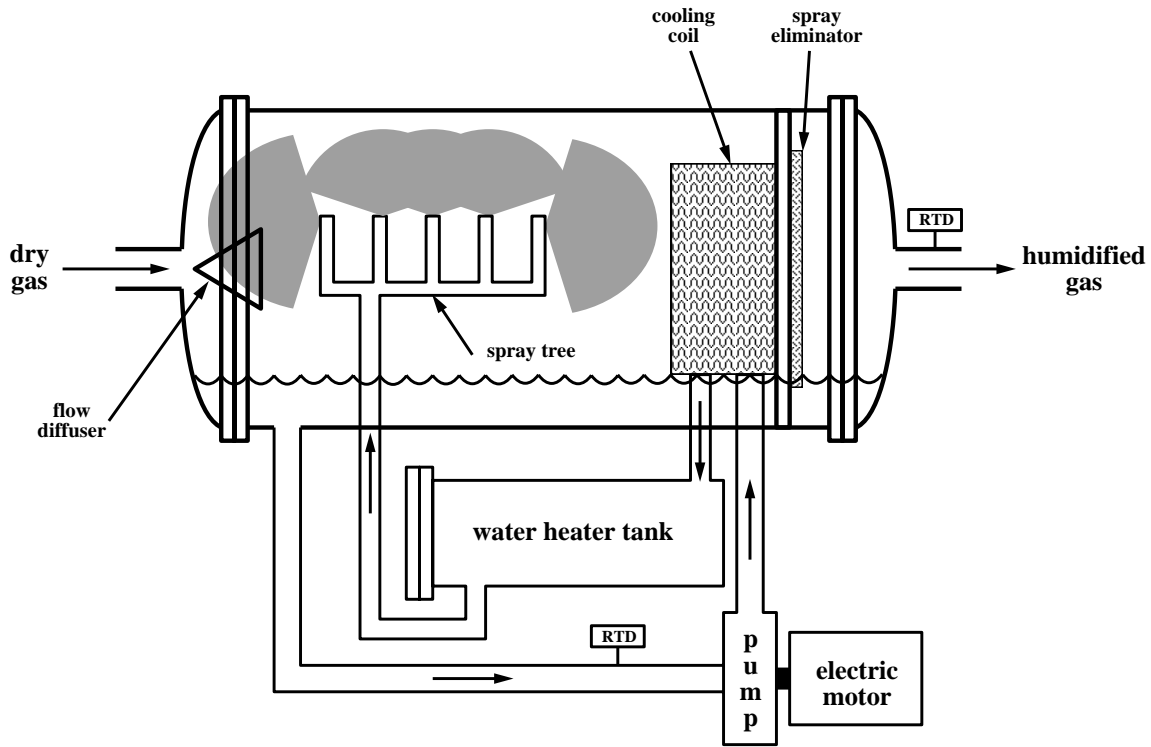

Figure 3. The EMCF saturator which adds water vapor to the flow.

Downstream from the saturator is a pressure transducer, a pressure reducing butterfly valve, and an associated pressure controller. This equipment maintains a pressure of 125 kPa in the saturator system when water vapor is being added to the gas stream. After the pressure reduction, a sample of the humidified gas is continuously pumped from the main pipeline, passed through a chilled mirror hygrometer, and returned to the main gas stream. A chilled mirror hygrometer measures the dew point temperature of a gas sample by cycling the temperature of a mirror and optically detecting the temperature at which condensation droplets form on the mirror surface. The pressure drop set up by the pressure reducing valve decreases the relative humidity from 100% to 80%, a range where the hygrometer has a better time response. The flow of water vapor is calculated from the dew point temperature, the pressure at the hygrometer, and the flow of the carrier gas (air or nitrogen).

The flow through the nozzle banks is kept critical (sonic at the throat) by maintaining a pressure ratio of at least two across the nozzle bank. The operating pressure of the saturator (125 kPa) sets the lower pressure limit for the air and nitrogen nozzles to 250 kPa. The upper pressure is limited by the gas supply and regulator systems and is approximately 750 kPa. The carbon dioxide and argon nozzle banks can be operated from 200 to 750 kPa since their downstream pressure is essentially 100 kPa.

After the saturator, care must be taken to maintain the main pipeline wall and gas temperatures at values greater than the dew point temperature of the gas mixture, else condensation will occur and the flow and composition through the meter under test will not be equal to those measured by the system. Therefore, all piping downstream of the saturator is wrapped with heat tape and is insulated. The temperatures of the main pipeline wall and gas are measured with RTD's, and the pipe wall temperature is maintained at a set point greater than the dew point temperature. Additionally, there is a valve located at the low point in the piping system where the operator can check for the presence of liquid water.

After the hygrometer, a metered carbon dioxide stream is mixed into the main gas stream. The source of the carbon dioxide is a manifold of six gas cylinders and the flow is metered with a bank of three nozzles similar to those previously described, but constructed with 1.25 cm tubing. Prior to entering the nozzle bank, the carbon dioxide goes through two stages of heating and pressure regulation to avoid formation of dry ice in the regulators. The tubing connecting the carbon dioxide nozzle bank to the main pipeline is heated with heat tape.

Next, the gas mixture enters a 90 kW electric circulation heater that heats the mixture to the temperature desired for flowmeter testing. This and all other heaters in the EMCF are controlled with proportional-integral-derivative (PID) control loops. After the large, final circulation heater, the metered argon flow is introduced into the main pipeline. The gas mixture then flows through 6 m of 5 cm tubing, a concentric enlargement to 7.5 cm tubing, a 180 degree turn, a low pressure-drop flow conditioner, and approximately 6 m of 7.5 cm tubing to the meter test section (80 diameters). The long runs of pipe and the flow conditioner allow thorough mixing of the gases and set up a fully developed, symmetric velocity profile before the flow enters the meter under test. Thus, meter errors due to distorted velocity profiles (installation effects) are eliminated. After the flow passes through the meter under test, it enters a flexible pipe that reaches into an exhaust duct operating much like a fume hood. The insertion depth of the flexible pipe into the exhaust duct can be adjusted so that there is negligible suction on the outlet of the meter under test. This set-up mimics the pressure conditions the meter is exposed to when it is used to measure vehicle exhaust flows.

A system of valves and piping allows the flow to be re-directed to piston provers, bell provers, and a Pressure-Volume-Temperature-time (PVTt) system located in other areas of the same building for calibration of the critical nozzles in the EMCF. In this way, the EMCF gas delivery systems can be utilized and the calibration is performed with the same

gas that will be metered later. The same piping configuration is used during calibration and meter usage so any installation effects on the critical nozzles are consistent. Since the nozzle banks are left in place for calibration, the temperature and pressure sensors are not handled, improving their calibration stability.

Argon is included in the gas mixture because it is present in the atmosphere at concentrations of approximately 1%, and therefore it flows through an engine intake and is a significant portion of the exhaust gas mixture. Carbon monoxide and oxygen are not included in the simulated exhaust for safety reasons and because once the catalytic converter of a vehicle "lights off" (about 3 minutes after engine startup), the concentrations of these components falls to less than 0.1% and their effect on meter output is negligible. The gas supplies for nitrogen, carbon dioxide, and argon are sized to permit continuous runs of more than 8 hours at mid range flow. The gases used in the EMCF have a purity of better than 99.99%.

Data Acquisition and Control System

The control system for the EMCF is based on a personal computer, a data acquisition (DAQ) card, a serial communications card, and a control program. Figure 4 shows that the DAQ card in the computer is connected to a signal conditioning and multiplexing chassis. The chassis holds cards which are wired to: 1) analog inputs, including 12 pressure transducers, 34 RTD's, and 11 inputs that can be used to acquire voltage or current signals from the meter under test, 2) analog outputs, which are used to transmit pressure regulator set points (to control flow) and heat tape (pipe wall heater) set points, and 3) digital outputs, which control the 30 valves which select the flow path through the EMCF or shut off gas flows.
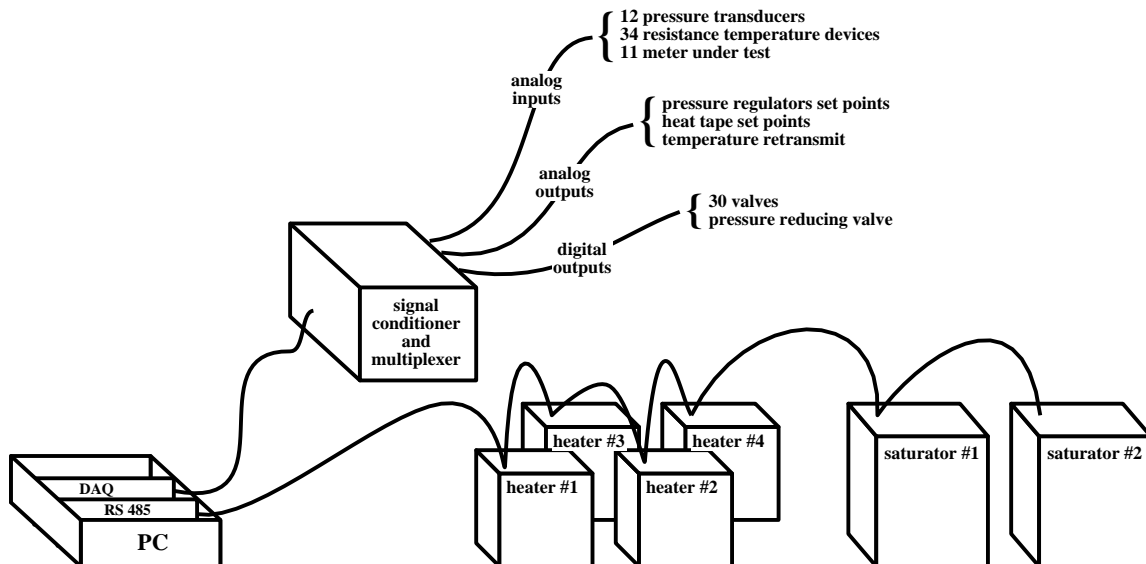

Figure 4. A schematic of the EMCF data acquisition and control system.

The electric circulation heaters and the two water heaters in the saturator are controlled by local, dedicated controllers. Set points and actual temperatures related to these heaters are communicated to the computer via an RS-485 interface. This distributes some of the control functions to locations outside the control program and leaves the software free for DAQ, display, and flow calculation functions.

Another example of the effort to distribute the control functions of the EMCF can be found in the flow controls illustrated in Figure 5. Recall that the flow through each critical nozzle is set by varying the pressure upstream of the nozzle. The computer DAQ system outputs a current to regulator A that is proportional to the calculated pressure set point. Regulator A adjusts the pressure in the dome of regulator B to control the pressure of the gas entering the nozzle bank. A pressure transducer connected to the regulated gas provides a current signal to regulator A that completes the control loop. Regulator A has software adjustable PID control capability. Hence the main computer software delivers the set point pressure necessary to achieve the desired flow to regulator A, and the regulator performs the control functions. One disadvantage to this system is that the flows entered by the user are nominal values, i.e., the actual flows may differ slightly from the set point because the control loop controls *pressure*, not flow. However, these differences can be calibrated out via the pressure set point calculations.
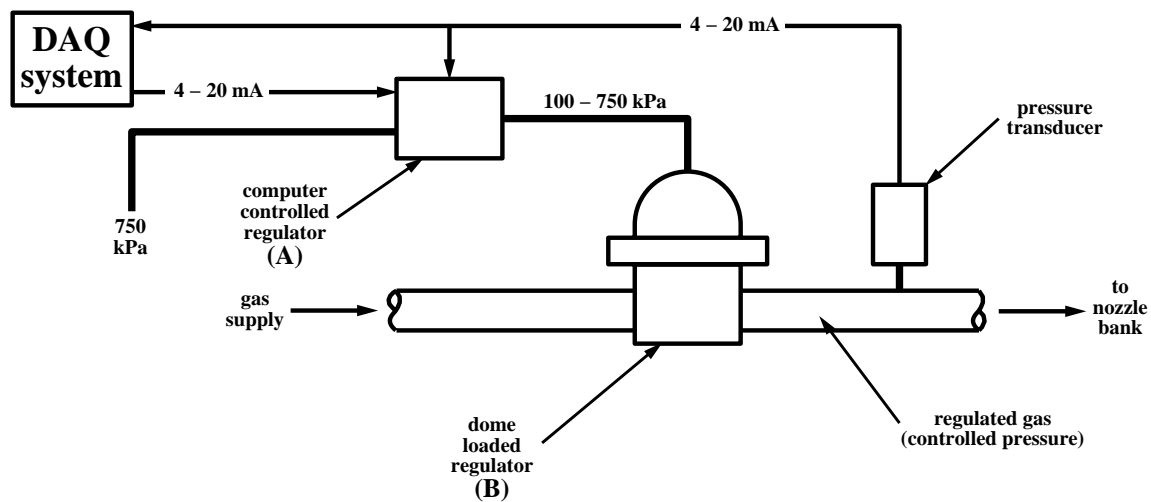

Figure 5. The EMCF nozzle pressure / flow control system.

The control program has a graphical user interface that presents a schematic diagram of the EMCF labeled with acquired temperatures, flows, etc., and with the active flow path highlighted. Quantities displayed on the main user interface include the temperatures and pressures along the active flow path, the percent of maximum heater output for each heater, the mass flow for each gas leg, the total volumetric and mass flow for the gas mixture, and the composition of the mixture by volume (or mole) fraction.

There are three modes of operation for the control software: manual, semi-automatic, and automatic. In manual mode, the operator uses mouse clicks to select the desired flow path and the program opens the appropriate valves. The user then controls the flow by typing in the set point pressure upstream from each nozzle in use. In semi-automatic mode, the operator uses a slider bar or types in the desired mass flow for each component gas. The program determines which nozzle to use, sets the valves to give that flow path, and calculates the pressure set point required to achieve the desired flow. In automatic mode, the program reads set point conditions of flow, temperature and composition from a "recipe" file previously set up by the user. The program implements the requested set point conditions, waits for flow and temperature stability criteria to be met, then takes 30 second averages of the EMCF and the meter under test readings and writes them to file. The raw data acquired at 60 Hz during the 30 second averaging period is written to a "burst" file. Log files hold readings gathered every 10 seconds from every sensor along the active flow path so that the time behavior of the EMCF can be studied. Other features of the software are strip charts of any of the sensor inputs and leak tests using valves to isolate various portions of the piping.

Calculation of Flow

This section describes the methods and equations used to calculate the mass flows of the pure gases through the critical nozzles, the mass flow of water vapor added by the saturator, and the volumetric flow of the final gas mixture.

Nozzle Mass Flow Calculation

The mass flow through a critical nozzle, $\dot{m}_{noz}$, can be calculated using the following equation: [1]

$$\dot{m}_{noz} = \frac{C_d \cdot C* \cdot P_0 \cdot \pi \cdot D^2}{4 \cdot \sqrt{R \cdot T_0}} \qquad (1)$$

where C_d is a coefficient of discharge, P_0 is the stagnation pressure upstream from the nozzle, D is the nozzle throat diameter, R is the gas constant (the universal gas constant divided by the gas molecular weight), and T_0 is the stagnation temperature upstream from the nozzle. The variable $C*$ is the critical flow factor, [2] a property of the gas and a known function of P_0 and T_0. For the EMCF software, tabular values of $C*$ have been fitted with a polynomial of the following form:

$$C* = b_0 + b_1 \cdot T_0 + b_2 \cdot T_0^2 + b_3 \cdot \frac{P_0}{T_0^2} \qquad (2)$$

where the polynomial coefficients, b_i, depend upon the gas in use.

Calibrations have been performed using NIST flow standards and data sets of the discharge coefficient versus the Reynolds number (Re) divided by the discharge coefficient have been calculated. A plot of such a C_d versus Re/C_d data set for one of the EMCF nozzles is shown in Figure 6. Presentation of nozzle flow calibration data in this manner allows the determination of the discharge coefficient from stagnation pressure and temperature measurements without need for an iterative calculation procedure. The quantity Re/C_d can be calculated by the following expression:

$$\frac{Re}{C_d} = \frac{C^* \cdot P_0 \cdot D}{\mu \cdot \sqrt{R \cdot T_0}} \tag{3}$$

where μ is the viscosity of the gas. Calibration data like that in Figure 6 were fitted with an equation of the following form:

$$C_d = a_0 + a_1 \cdot \left(\frac{Re}{C_d}\right)^{-a_2} \tag{4}$$

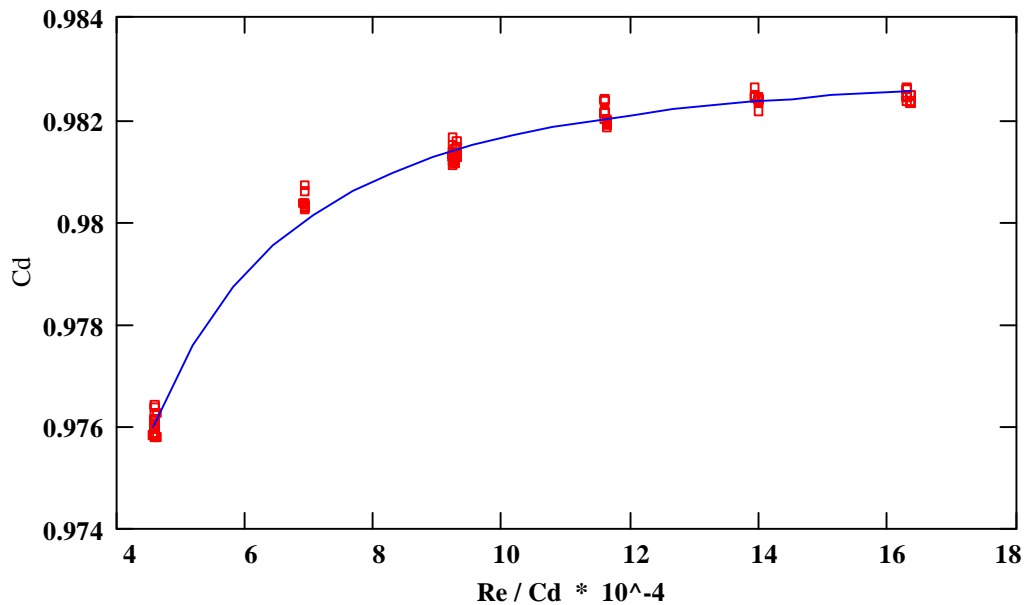where the a_i's are best fit coefficients that differ for each nozzle.

Figure 6. Calibration data for an EMCF nozzle and the equation (4) curve fit.

To calculate the flow from a critical nozzle in the EMCF, the following steps are followed: 1) acquire the stagnation pressure and temperature, 2) calculate the viscosity and the critical flow factor from tabular data, 3) calculate Re/C_d via equation (3), 4) calculate C_d with equation (4), and 5) calculate the mass flow using equation (1).

The flow calculation procedure described above is simple and robust. As long as the same correlations for C^* and μ are used for both nozzle calibration and for subsequent flow calculations, then the experimental errors in their determination do not lead to error in the mass flow measurements. Errors in the pressure and temperature measurements do not affect the accuracy of the mass flow measurement either, as long as the sensor readings are *repeatable*: errors in the temperature and pressure sensor calibrations are corrected by the discharge coefficient. However, it is important to recognize that sensors are *not interchangeable* in the system, and if there is a sensor failure it is necessary to perform a flow calibration, not just a temperature or pressure sensor calibration.

Water Mass Flow Calculation

The flow of water vapor in the EMCF is calculated from the dew point temperature, T_{dp}, measured by the optical hygrometer, the pressure measured at the hygrometer, P_{hygr}, and the mass flow of the carrier gas (air or nitrogen). The vapor pressure of water can be calculated from the dew point temperature using the following correlation:

$$P_v = P_c \cdot \exp\left(\frac{T_c}{T_{dp}} \left(c_0 \cdot \tau + c_1 \cdot \tau^{1.5} + c_2 \cdot \tau^3 + c_3 \cdot \tau^{3.5} + c_4 \cdot \tau^4 + c_5 \cdot \tau^{7.5} \right) \right) \qquad (5)$$

where P_c and T_c are the critical pressure and temperature of water, $\tau = 1 - T_{dp}/T_c$, and the c_i's are coefficients which can be found in the literature. [3] The mass flow of water can be calculated by the equation:

$$\dot{m}_{H2O} = \dot{m}_{CG} \cdot \frac{MW_{H2O}}{MW_{CG}} \cdot \frac{f \cdot P_v}{\left(P_{hygr} - f \cdot P_v \right)} \qquad . \qquad (6)$$

In the previous equation, MW is molecular weight, the subscript H2O represents water, and CG the carrier gas. The variable f (the enhancement factor) accounts for the greater saturation vapor pressure of water when mixed with a carrier gas than for pure water alone. The enhancement factor is a function of the dew point temperature and the pressure at the hygrometer, and its value varies from 1.0038 to 1.0057 for the conditions available in the EMCF. [4]

Total Mass and Volumetric Flow Calculation

The mass flow of the total gas mixture ($\dot{m}_{EMCF}$) is readily calculated by summing the mass flows of the pure gas components,

$$\dot{m}_{EMCF} = \dot{m}_{Air} + \dot{m}_{N2} + \dot{m}_{CO2} + \dot{m}_{Ar} + \dot{m}_{H2O} \qquad . \tag{7}$$

However, the total volumetric flow is *not* precisely equal to the sum of the volumetric flows of the pure gas components due to molecular interactions between the different species, or virial effects. [5] Virial effects are more significant when the temperature is low, the pressure is high, or a polar molecule like water is present in the mixture. For the range of conditions available in the EMCF, neglecting virial effects could lead to errors of about 0.2%. Therefore it is necessary to obtain the density of the gas mixture, ρ_{mix}, including virial effects, and to use that density when calculating the volumetric flow of the mixture:

$$\dot{V}_{EMCF} = \frac{\dot{m}_{EMCF}}{\rho_{mix}} \qquad . \tag{8}$$

The second virial coefficient for a mixture of argon, carbon dioxide, nitrogen, oxygen, and water vapor can be calculated using the following expression, which accounts for only the significant species-pair molecular interactions: [6,7]

$$B_{mix} = B_0 \cdot x_{N2}^2 + 2 \cdot B_1 \cdot x_{N2} \cdot x_{O2} + 2 \cdot B_2 \cdot x_{N2} \cdot x_{CO2} + 2 \cdot B_3 \cdot x_{N2} \cdot x_{H2O}$$

$$+ 2 \cdot B_4 \cdot x_{O2} \cdot x_{H2O} + B_5 \cdot x_{CO2}^2 + 2 \cdot B_6 \cdot x_{CO2} \cdot x_{H2O} + B_7 \cdot x_{H2O}^2 \tag{9}$$

where the B_i's are the virial coefficients for the species pairs, equal to -5.0, -11.2, -41.7, -43.0, -61.1, -131.9, -142.0, and -1249.0, respectively, and B_{mix} is in units of cm^3/mole. Oxygen interactions with other components appear in equation (9) so that it can be used to calculate density for mixtures for which air is an ingredient. However, the oxygen-oxygen interaction is not in equation (9) as it is a rather small contributor to B_{mix}. The B_i's are normally functions of temperature, but the fact that the objective is to convert the mass flow to the *standard* volumetric flow (i.e., at a particular temperature and pressure, $T = 293.15$ K, $P = 101.325$ kPa) and not the volumetric flow at some arbitrary temperature, reduces the B_i's to constants and simplifies the algorithm.

The composition-weighted molecular weight (MW_{mix}) is calculated, and the density of the mixture is:

$$\rho_{mix} = \frac{P \cdot MW_{mix}}{R_u \cdot T \cdot \left(1 + B_{mix} \cdot \dfrac{P}{R_u \cdot T}\right)} \tag{10}$$

where R_u is the universal gas constant. For the standard temperature and pressure conditions, equation (10) can be simplified to:

$$\rho_{mix} = \frac{MW_{mix}}{2.4055 \cdot 10^4 + B_{mix}} \tag{11}$$

where ρ_{mix} has the units g/cm^3.

EMCF Uncertainty Analysis

The total mass flow entering the meter under test can be expressed as:

$$\dot{m}_{EMCF} = \sum_{gas} \frac{C_d \cdot C^* \cdot P_0 \cdot \pi \cdot D^2}{4 \cdot \sqrt{R \cdot T_0}} \; + \; \dot{m}_{CG} \cdot \frac{MW_{H2O}}{MW_{CG}} \cdot \frac{f \cdot P_v}{\left(P_{hygr} - f \cdot P_v\right)} \; - \; \frac{\partial \rho_c}{\partial t} \cdot V_c \tag{12}$$

The first two terms of equation (12) are the sums of the nozzle mass flow measurements and the water flow measurement as described in the prior section and together they comprise the standard flow as calculated by the EMCF. The index "gas" indicates summation over all of the dry gases (metered by critical nozzles). The third term accounts for "storage" effects due to density changes in the pipe volume connecting the EMCF nozzles to the meter under test. The variable V_c is the connecting volume, and $\partial \rho_c / \partial t$ is the time derivative of the density of the gas in the connecting volume.

The uncertainty of the EMCF flows and compositions can be calculated by considering: 1) the uncertainty of the nozzle mass flow measurements, 2) the uncertainty of the water mass flow measurement, 3) storage effects in the connecting volume upstream from the meter under test, 4) the "purity" of the gas mixture or dilution effects after composition changes, and 5) the uncertainty of the conversion from mass to volumetric flow (mixture density). Leaks from the EMCF will be considered negligible since pressure tests of the piping system are carried out periodically. Uncertainties in the water flow due to condensation will be assumed equal to zero as well, since a valve at the piping low point is used to check for the presence of liquid water. Uncertainties due to impurity of the gas supplies will be neglected since their purity is better than 99.99%.

The uncertainty analysis will be performed by obtaining one standard deviation values for the various uncertainty components, combining them by the root-sum-squares method (RSS), and multiplying this *combined* uncertainty by a coverage factor of 2 to obtain an *expanded* uncertainty with a 95% confidence interval. [8] The uncertainty of the components are gathered from statistical analysis of experimental measurements where practical, and from instrument specifications and engineering estimates otherwise.

Nozzle Mass Flow Uncertainty

The flow calibration and calculation methods (described in a prior section) remove uncertainties due to the critical flow factor, molecular weight, viscosity, calibration errors in the pressure and temperature sensors, and the piping arrangement upstream from the meter which are all consistent during a nozzle calibration and its usage as a standard. Sources of uncertainty *do* include the uncertainty of the flow standards used to calibrate the nozzles, scatter observed in the nozzle discharge coefficient data, and any drift that might occur in the temperature and pressure measurements between nozzle flow calibrations. The effect of room temperature variations on the pressure sensors must be considered as well.

The uncertainty of the flow standards used to calibrate the nozzles is 0.22% or less, with a 95% confidence interval. [9] The scatter in the nozzle Cd data was measured by taking the standard deviation of the residuals between the best fit curve (equation (4)) and the experimental calibration data. The largest standard deviation value for any of the nozzles was 0.25% and this value will be used for all of them. Note that some of this scatter is due to variations in the flow standard, an uncertainty that has already been accounted for, but no correction will be made in order to keep the uncertainty analysis conservative.

The uncertainty in the nozzle pressure measurements due to drift between flow calibrations and room temperature variations is estimated to be 0.06% based on the transducer manufacturers specifications and calibration experience. Based on manufacturer's specifications, the gas temperature sensor drift is estimated to be 0.02% or better. Combining the four uncertainty components by RSS gives a nozzle mass flow measurement uncertainty of 0.34%.

Water Mass Flow Uncertainty

Examining equations (5) and (6), it is apparent that the uncertainty of the water mass flow measurement has components due to the uncertainty in the carrier gas mass flow, the value of the water vapor pressure, the value of the enhancement factor, and the measured hygrometer pressure. The vapor pressure in turn has uncertainties due to the dew point temperature uncertainty and the quality of the equation used to calculate the vapor pressure. Sampling errors due to diverting a portion of the main flow stream to the

hygrometer are considered negligible since the gas in the main pipeline should be quite homogeneous and the sampling tube is well heated.

The major component of the water mass flow uncertainty is due to uncertainty in the dew point temperature measurement made by the optical hygrometer. Examination of calibration data for the instrument as compared to the NIST humidity standard, as well as calibration data from the hygrometer manufacturer, leads to a dew point temperature uncertainty of 0.20 K. The sensitivity of the water vapor pressure ($\partial P_v / \partial T_{dp}$) becomes large at high dew point temperatures (i.e., a small change in dew point temperature leads to a relatively large change in the water vapor pressure, and in turn the water mass flow). At a dew point temperature of 327 K (the maximum water concentration for the facility, $x_{H2O} = 0.15$), the dew point temperature uncertainty of 0.20 K leads to a vapor pressure uncertainty of 0.96%.

Inspection of the uncertainty estimates provided in the literature [10] for equation (5) indicates that the uncertainty of the vapor pressure equation is less than 0.01% and therefore can be considered negligible here. The literature regarding the the enhancement factor gives uncertainties of 0.03% or less over the operating range of the EMCF. [4, 11]

Unlike the pressure sensors used for the nozzle flow calculations, the absolute calibration of the transducer used to measure P_{hygr} is critical: there is no *in situ* calibration of the water mass flow to correct for these pressure errors. The pressure transducer is periodically calibrated with a piston pressure gage. The uncertainty of the pressure measurements, considering the uncertainty of the calibrator, the standard deviation of the calibration residuals, the drift between calibrations, and room temperature variation effects is 0.06%. Combining the vapor pressure, enhancement factor, carrier gas mass flow, and hygrometer pressure uncertainties by RSS gives a maximum combined uncertainty for the water mass flow of 1.02%.

Uncertainty Due to Storage Effects

A considerable volume is contained by the piping, saturator vessels, and heater vessels that carry the gas from the EMCF nozzles to the meter under test, i.e., the connecting volume, V_c. If the density of the gas in the connecting volume is increasing (due to decreasing temperature or increasing pressure), then gas is effectively "stored" in the connecting piping, and the mass flow of gas into the meter under test is actually less than that measured by the EMCF. Conversely, if the density in the connecting volume is decreasing, more flow is entering the meter under test. It is important to recognize that the gas does not have to attain identical values of temperature and pressure throughout the connecting volume to make the storage effects term zero. Rather, the distribution of temperature and pressure within the system must have reached steady state, so that changes in density with respect to time are zero throughout the system.

In practice, flow data is collected only after certain flow and temperature stability criteria have been met, at least several minutes after a change in the flow or temperature set points. The quantity that is of interest is the rate of change of density during the 30 second data collection interval after the stability criteria have been met. Changes in pressure within the connecting volume are negligible, but the effects of temperature changes on the connecting volume density must be considered.

Temperature data from log files and burst files for the sensors at numerous locations along the connecting volume were examined to establish the magnitude of the temperature changes during an averaging period. Locations where temperature measurements in the connecting volume are available include: the nozzle inlet, the saturator inlet, the outlets of both saturator vessels, either side of the pressure reducing valve, the final heater outlet, and either side of the meter under test. Based on the temperature traces from these locations, a reasonable assumption for a one standard deviation change in the connecting volume temperature over the 30 second averaging period is 0.15 K. This temperature change results in a $\partial \rho_c / \partial t$ value of 2.2 x 10^{-5} g/(liter s). This value was calculated using a maximum mixture density for the EMCF of 1.3 g/liter.

The size of the connecting volume depends upon what flow path is in use. The three flow paths to consider are: 1) the saturator bypass, 2) the small saturator, and 3) the large saturator. The connecting volumes for these paths are 135, 210, and 750 liters respectively. All three paths share the final heater volume (78 liters) and the long runs of insulated 5 and 7.5 cm tubing (48 liters). Calculating the mass flows due to storage effects with the quantities given above gives 0.0030, 0.0046, and 0.0165 g/s for the three flow paths. When the bypass or small saturator are in use, the minimum flow through the EMCF is 1.14 g/s and the minimum flow at which the large saturator is used is 52 g/s. Using these minimum flows, the storage effect mass flows lead to uncertainties of 0.26%, 0.40%, and 0.03% for the three flow paths. It should be noted that the flows due to storage effects decrease with increasing flow set points, and therefore this uncertainty component becomes quite small at the larger flows of the facility.

Uncertainty Due to Dilution Effects

When the EMCF has been used to produce humidified air, and then the operator switches the composition to humidified nitrogen, the nitrogen must "wash" the air out of the saturator vessels, the final heater, and the connecting piping. The new flow composition does not move through the volume as a plug flow with a step change in composition at the flow front. Instead the old and new compositions mix together, and the new composition is asymptotically approached at the inlet to the meter under test through a dilution process. This same process applies whenever the mixture composition is changed, for instance if the concentrations of carbon dioxide or argon are changed.

If perfect mixing within the connecting volume is assumed, then the mixing problem is governed by a first order ordinary differential equation. [12] The concentration of a particular gas at the EMCF outlet can be calculated via an exponential function:

$$x_{out} = x_{in} \cdot \left(1 - \exp\left(\frac{-\dot{V} \cdot t}{V_c}\right)\right) \qquad . \qquad (13)$$

Hence the concentration of each gas entering the meter under test (x_{out}) asymptotically approaches the concentration as calculated from the nozzle flows (x_{in}). The time constant for this dilution process is equal to the connecting volume divided by the volumetric flow.

Equation (13) can be used to calculate the necessary "wait times" before data collection commences. One can imagine the connecting volume to be initially filled with some gas "x" which is washed out by the simulated exhaust flow. A measure of how closely the gas mixture entering the meter under test approaches the composition as calculated by the EMCF, is a summation of the x_{out} values for all the simulated exhaust components. This summation asymptotically approaches the value of 1.0 and the concentration of gas "x" in the connecting volume falls to 0.0. The summation has been calculated for several test conditions (using the appropriate connecting volume for each gas) and the times required for the outlet composition to reach 99.9% of the composition as calculated by the EMCF are presented in Table 3.

The results in Table 3 show that low flows (particularly ones that include the small argon flow) take too long (1.5 hrs) to reach an acceptable "purity" at the EMCF outlet. Therefore, the operating procedures for the EMCF call for first running the EMCF at the highest flow and the desired composition for 10 minutes. The analysis (see Table 3) shows that when using the highest flow, the 99.9% composition level is reached in 4 minutes or less. Using the maximum flow first establishes the desired composition in the connecting volume and dilution effects are thereafter negligible. Dilution will effect the EMCF flow uncertainty through the mixture density and through the water mass flow calculation where the molecular weight of the carrier gas is an issue. However, if the 99.9% purity wait times are followed, these uncertainties are negligible, and hence a "dilution effects" term does not appear in the combined uncertainty equation.

Combined Uncertainty of EMCF Mass and Volumetric Flow Measurements

When calculating the combined uncertainty for the mass flow of the EMCF gas mixture, the flow uncertainty of each pure gas stream should be weighted by the mass fraction of that gas. This can be shown by considering the mass flow uncertainty of the gas mixture in dimensional quantities, say g/s:

$$\Delta \dot{m}_{EMCF} = \sqrt{\left(U_{noz} \cdot \dot{m}_{Air}\right)^2 + \left(U_{noz} \cdot \dot{m}_{N2}\right)^2 + \left(U_{noz} \cdot \dot{m}_{CO2}\right)^2 + \ldots + \Delta \dot{m}_{storage}^2} \qquad (14)$$

where U represents the fractional flow uncertainty for the particular gas. Analogously, the % uncertainty of the EMCF mass flow measurement is:

$$U\%_{\dot{m}\_EMCF} = \sqrt{\sum_{gas}\left(U\%_{noz}\cdot\frac{\dot{m}_{gas}}{\dot{m}_{EMCF}}\right)^2 + \left(U\%_{H2O}\cdot\frac{\dot{m}_{H2O}}{\dot{m}_{EMCF}}\right)^2 + \left(U\%_{storage}\right)^2} \quad (15)$$

where $U\%$ is the percent uncertainty.

The results of the mixture density calculation given in equations (9) - (11) have been compared to data in literature and a reasonable one standard deviation uncertainty is 0.02%. [13,14] This value is small enough relative to the mass flow uncertainty that it can be neglected and it is safe to assume that the mass and volumetric flow uncertainties are equal.

Table 3 lists the combined and expanded uncertainties (95% confidence values) for several postulated mixture compositions and flows available in the EMCF. The uncertainties in Table 3 were not calculated assuming that the water mass flow and storage effect uncertainties were at their maximum values: the values of $\partial P_v/\partial T_{dp}$ and V_c for the particular test condition were used.

Table 3. Uncertainty of the EMCF mass flow and the wait time to reach 99.9% composition purity for various test conditions.

Volumetric Flow (slm)	x_{Air}	x_{N2}	x_{CO2}	x_{Ar}	x_{H2O}	Combined Uncertainty (%)	Expanded Uncertainty (%)	99.9% Wait Time (min)
60	0	1	0	0	0	0.43	0.86	16
70	0	0.85	0.15	0	0	0.35	0.70	58
70	0	0.85	0	0	0.15	0.50	1.00	58
80	0	0.73	0.14	0.01	0.12	0.40	0.80	105
1000	0	0.73	0.14	0.01	0.12	0.28	0.56	9
2000	0	0.73	0.14	0.01	0.12	0.27	0.54	4
6000	0.85	0	0	0	0.15	0.33	0.66	1

The first test condition in table 3, pure nitrogen at 60 slm, gives the uncertainty for the minimum flow of the facility, 0.86%. This case makes it clear that the EMCF should not be used to establish standard flows of pure carbon dioxide or argon because the uncertainty due to storage effects is too large for flows smaller than about 60 slm.

The 70 slm flows in table 3 demonstrate the uncertainty of the EMCF under two composition conditions that might be used to test for meter sensitivity to gas composition.

The 15% concentrations of carbon dioxide and water are approximately the maximum values found in vehicle exhaust. The greatest uncertainties in the EMCF flows (1.00%) occur at the lowest flows that contain water. This is primarily due to the saturator vessel being included in the connecting volume.

The three test conditions at 80, 1000, and 2000 slm in table 3 give the EMCF flow uncertainties for a gas composition which is typical of auto exhaust. The uncertainties for these flows (which represent the smallest, mid-range, and largest simulated exhaust flows for the facility) are 0.80, 0.56, and 0.54%. The last condition in table 3 shows the uncertainty for the largest flow (humidified air) available in the EMCF (0.66%).

Conclusions

The NIST Exhaust Meter Calibration Facility generates flows of hot gas mixtures by metering pure gas streams, mixing them, and heating the mixture. The facility can be used to run performance tests and calibrations of flow meters used to measure vehicle exhaust or the flow from other carbon fuel combustion processes. The facility is a unique testbed for research on the measurement of gas flows with variable composition and temperature.

The uncertainty of the EMCF flow is 1% of reading or less, depending on the magnitude of the flow and the composition of the gas mixture. The largest sources of uncertainty are the water mass flow measurement and storage effects due to density changes in the connecting volume. Analysis of dilution effects dictates that the flow should be run at the desired composition and the highest flow for more than 4 minutes to achieve 99.9% composition purity at the inlet to the meter under test.

Acknowledgments

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