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Turbine Flowmeter Fuel Flow Calculations

RATIONALE

One of the cited references has been revised - a common calibration curve for Jet-A and Jet-A1 fuels has been replaced by two calibration curves, one for each. The revision will address this change, and remove any ambiguity that may arise by referring to the old document.

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1. SCOPE

This SAE Aerospace Recommended Practice (ARP) provides to the aerospace industry a procedure for the consistent and accurate calculation of fuel flow using turbine flowmeters during development, production, and post overhaul/repair gas turbine engine testing.

1.1 Purpose

One of the methods of measuring fuel-flow-rate in a test-environment is by means of a turbine flow-meter. This recommended practice outlines a process for the calculation of flow-rate when a turbine flow-meter is used for the measurement.

2. REFERENCES

2.1 Applicable Documents

The following publications form a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of other publications shall be the issue in effect on the date of the purchase order. In the event of conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

2.1.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or +1 724-776-4970 (outside USA), www.sae.org.

ARP741 Turbofan and Turbojet Gas Turbine Engine Test Cell Correlation

2.1.2 API Publications

Available from API, 1220 L Street, NW, Washington, DC 20005-4070, Tel: 202-682-8000, www.api.org.

Manual of Petroleum Measurement Standards, Ch. 4: Proving Systems

Manual of Petroleum Measurement Standards, Ch. 11.2.1: Compressibility Factors for Hydrocarbons: 0-90 API Gravity Range

Manual of Petroleum Measurement Standards, Ch. 12.2.5.1: Correction for the Effect of Temperature on Steel, Cts

Manual of Petroleum Measurement Standards, Ch. 12.2.5.2: Correction for the Effect of

Pressure on Steel, Cps

Technical Data Book - Petroleum Refining, API Procedure 11A5.7, Liquid Viscosity of High-Molecular-Weight Pure and Mixed Hydrocarbons at High Pressure

2.1.3 ASTM Publications

Available from ASTM International, 100 Barr Harbor Drive, P.O. Box C700, West Conshohocken, PA 19428-2959, Tel: 610-832-9585, www.astm.org.

ASTM D240 Standard Test Method for Heat of Combustion of Liquid Hydrocarbon Fuels by Bomb Calorimeter

ASTM D287 Standard Test Method for API Gravity of Crude Petroleum and Petroleum Products (Hydrometer Method)

ASTM D341 Standard Viscosity-Temperature Charts for Liquid Petroleum Products

- ASTM D445 Standard Test Method for Kinematic Viscosity of Transparent and Opaque Liquids (and the Calculation of Dynamic Viscosity)
- ASTM D1018 Standard Test Method for Hydrogen in Petroleum Fractions
- ASTM D1217 Standard Test Method for Density and Relative Density (Specific Gravity) of Liquids by Bingham Pycnometer
- ASTM D1250 Standard Guide for Petroleum Measurement Tables, Volume X: Background, Development, and Implementation Procedures
- ASTM D1298 Standard Practice for Density, Relative Density (Specific Gravity), or API Gravity of Crude Petroleum and Liquid Petroleum Products by Hydrometer Method
- ASTM D2382 Standard Test Method for Heat of Combustion of Hydrocarbon Fuels by Bomb Calorimeter (High Precision Method)
- ASTM D3701 Standard Test Method for Hydrogen Content of Aviation Turbine Fuels by Low Resolution Nuclear Magnetic Resonance Spectrometry
- ASTM D4052 Standard Test Method for Density and Relative Density of Liquids by Digital Density Meter
- ASTM D4809 Standard Test Method for Heat of Combustion of Liquid Hydrocarbon Fuels by Bomb Calorimeter (Intermediate Precision Method)
- 2.1.4 Coordinating Research Council, Inc., Aviation Fuel Properties, CRC Report No. 530.
- 2.1.5 Craft, D. William, High Accuracy Fuel Flowmeter - Final Report - Phase IIC and Phase III, The Mass Flowrate Calibration of High Accuracy Fuel Flowmeters, NASA CR 187108, February, 1992.
- 2.1.6 Grabe, W., Fuel Flow Measurement in Gas Turbine Testing, National Research Council of Canada, TR-ENG-001, NRC No. 29808, 1988/08.
- 2.1.7 Hochreiter, H. M., Dimensionless Correlation of Coefficients of Turbine-Type Flowmeters, ASME Paper No. 57-A-63, Transactions of the ASME, October 1958.
- 2.1.8 IEEE Std. 268 - 1982, IEEE Standard Metric Practice, Institute of Electrical and Electronics Engineers.
- 2.1.9 Mattingly, G. E., The Characterization of a Piston Displacement-Type Flowmeter Calibration Facility and the Calibration and Use of Pulsed Output Type Flowmeters, Journal of Research of the National Institute of Standards and Technology, Volume 97, Number 5, September-October 1992, pp. 509-531.
- 2.1.10 Olivier, Paul D., Determination of Turbine Flowmeter Usable Turndown, Proceedings of National Conference of Standards Laboratories Workshop and Symposium, July 1995.
- 2.1.11 Ruffner, Donald F, and Olivier, Paul D., Improved Turbine Meter Accuracy by Utilization of Dimensionless Data, Proceedings of National Conference of Standards Laboratories Workshop and Symposium, August 1994.
- 2.1.12 Schoonover, Randall M. and Jones, Frank E., Air Buoyancy Correction in High-Accuracy Weighing on Analytical Balances, Journal of Analytical Chemistry, Volume 53, Number 6, May 1981, pp. 900-902.
- 2.1.13 Shafer, M. R. and Ruegg, F. W., Liquid-Flowmeter Calibration Techniques, ASME Paper No. 57-A-70, Transactions of the ASME.

2.2 Nomenclature

API	American Petroleum Institute
ASTM	American Society for Testing and Materials
B_o	buoyancy adjustment to convert from "in-vacuo" to "in-air" (dimensionless)
C_{pfd}	pressure correction on fuel density (dimensionless)
C_{pfv}	pressure correction on fuel viscosity (dimensionless)
C_{pk}	pressure correction factor due to flowmeter expansion to obtain K_{op} (dimensionless)
C_{pr}	pressure correction factor due to flowmeter expansion to obtain R_{op} (dimensionless)
C_{tk}	temperature correction factor due to flowmeter expansion to obtain K_{op} (dimensionless)
C_{tr}	temperature correction factor due to flowmeter expansion to obtain R_{op} (dimensionless)
D	bore diameter of flowmeter (in or m), measured at T_{cal}
E	modulus of elasticity of the flowmeter meter material (psi or bar)
f	flowmeter frequency (Hz or cycles/s)
F	compressibility factor of the fuel (1/psia or 1/bar-a)
HYC	stem correction for glass hydrometer thermal expansion (dimensionless)
K , K-factor	flowmeter coefficient (cycles/US-gal or cycles/L)
K_{op}	K-factor at operating conditions (cycles/US-gal or cycles/L)
LHV	measured lower heating value (Btu/lb or kJ/kg)
LHV_{cf}	lower heating value correction factor (dimensionless)
LHV_{ref}	reference lower heating value (Btu/lb or kJ/kg)
p_{atm}	atmospheric pressure at operating conditions (psia or bar-a)
$p_{atm, cal}$	atmospheric pressure during flowmeter calibration (psia or bar-a)
p_{cal}	absolute pressure of fuel at the flowmeter during calibration (psia or bar-a)
p_{eq}	equilibrium pressure of the fuel (psia or bar-a)
p_{gage}	gage pressure of fuel at the flowmeter during operation (psig or bar-g)
p_{op}	absolute pressure of fuel at the flowmeter during operation (psia or bar-a)
Q	fuel volume flow rate (US-gal/s or L/s)
RD	relative density formerly referred to as specific gravity (dimensionless)

RF	radio frequency
Ro	Roshko number (dimensionless)
Ro _{op}	Roshko number at operating conditions (dimensionless)
St	Strouhal number (dimensionless)
St _{op}	Strouhal number at operating conditions (dimensionless)
t	wall thickness of the flowmeter (in or m)
T _{cal}	calibration temperature of the flowmeter (°F or °C)
T _{ref}	reference temperature (60 °F or 15 °C)
T _{op}	operating temperature of the fuel at the flowmeter (°F or °C)
T _{op,abs}	absolute operating temperature of the fuel at the flowmeter (°R or °K)
T _s	temperature of the fuel sample (°F or °C)
T _{s,abs}	absolute temperature of the fuel sample (°R or °K)
UVC	universal viscosity curve
VCF	volume correction factor (dimensionless)
W _{f,t}	true fuel mass flow rate (lbm/h or kg/h)
W _{f,LHV}	LHV corrected fuel mass flow rate (lb/h or kg/h), i.e., true fuel mass flow rate referenced to a standard heat of combustion

2.3 Greek Symbols

$\alpha_{F,T_{ref}}$	coefficient of thermal expansion of the fuel at reference temperature (T _{ref}) (1/°F or 1/°C)
α_l	coefficient of linear thermal expansion of the flowmeter (1/°F or 1/°C)
δ	(observed inlet total absolute pressure)/(absolute pressure of ISO sea level standard day reference atmosphere) (dimensionless)
μ_s	dynamic viscosity of the fuel sample (centipoise)
ν_{op}	kinematic viscosity of the fuel sample corrected for operating temperature (T _{op}) and pressure (p _{op}) (cSt)
ν_s	kinematic viscosity of the fuel sample (cSt)
ν_{Top}	kinematic viscosity of the fuel sample corrected for operating temperature (T _{op}) (cSt)
θ	(observed inlet total absolute temperature)/(absolute temperature of ISO sea level standard day reference atmosphere) (dimensionless)
ρ_a	air density (kg/m ³)
ρ_{op}	density of the fuel corrected for operating temperature (T _{op}) and pressure (p _{op}) (kg/m ³)

ρ_s	fuel sample density (kg/m ³)
$\rho_{s,hyc}$	fuel sample density corrected for glass hydrometer thermal expansion (kg/m ³)
ρ_{Top}	density of the fuel corrected for operating temperature (T_{op}) (kg/m ³)
$\rho_{Top,gcc}$	density of the fuel corrected for operating temperature (T_{op}) (g/cm ³)
ρ_{ref}	density of the fuel at reference temperature (T_{ref}) (kg/m ³)
$\rho_{ref,gcc}$	density of the fuel at reference temperature (T_{ref}) (g/cm ³)
ρ_w	balance weight density (kg/m ³)
$\rho_{water,ref}$	density of water at reference temperature in vacuo (T_{ref}) (kg/m ³)

3. BACKGROUND

A variety of fuel flow determination methods have evolved throughout the aerospace industry. Most fuel property and flow measurement methods as well as temperature/pressure corrections have been based on established techniques published in the literature. Often, however, notable differences in measured fuel properties and calculated fuel flow have become apparent upon comparison of results between parties. A portion of these differences could be justifiably attributed to experimental uncertainty and the reproducibility of the measurement technique in different laboratories. Other disparities, due to differences in the measurement and/or correction techniques, have resulted in considerable time and effort being devoted to the justification and/or validation of each facility's methodology.

A procedure adopted by the entire industry would provide a common basis for the consistent and accurate calculation of fuel flow and help alleviate points of confusion or inconsistency. As such, the procedure defined herein is based on ASTM and API standard test methods as well as temperature and pressure correction methodologies and can be used to establish the physical quantities required in the determination of fuel flow such as relative density, viscosity, lower heating value and for calibrating turbine flowmeters.

The data and processes outlined in this document represent a recommended practice for the calculation of fuel flow from measurements using a turbine flow meter. Minor deviations to the calculation process and/or data used in the correction of fuel property state conditions may differ for a particular fuel or class of fuels or even a specific fuel meter's operating condition. Allowances should be made under those conditions to support individual laboratory-data and experience.

4. INTRODUCTION

4.1 True Fuel Mass Flow Rate

The basic building blocks for determining fuel flow with volumetric flowmeters are shown in Equation 1. A mass per unit volume quantity (density) is multiplied by a volume per unit time quantity (volume flow rate) to obtain true mass per unit time (true mass flow rate).

$$\frac{\text{mass}}{\text{volume}} * \frac{\text{volume}}{\text{time}} = \frac{\text{mass}}{\text{time}} \quad (\text{Eq. 1})$$

or similarly,

$$\text{density} * \text{volume flow rate} = \text{true mass flow rate} \quad (\text{Eq. 2})$$

Fuel sample density is measured and/or reported at a reference temperature and pressure. If the fuel is subjected to conditions at the flowmeter during engine operation that are different from those which existed at reference conditions, then temperature and/or pressure corrections should be applied to the density term. The corrections to fuel density are not needed when an in-line digital density meter is used and is located sufficiently close to the flowmeter so that the fuel can be assumed to be at the same temperature and pressure at both the digital density meter and the flowmeter.

The volume flow rate is obtained using the flowmeter's calibration curve. The calibration curve is valid at the temperature and pressure of calibration for the flowmeter. However, during engine operation, if the flowmeter is subjected to conditions different from those at calibration, then appropriate temperature and pressure corrections to account for changes in flowmeter geometry should be applied to the calibration data.

Also, as discussed in 4.3, the calibration curve is a function of the fluid viscosity, which must be known to properly use the curve. Temperature and pressure corrections should be applied to determine fluid viscosity at engine operating conditions. The viscosity corrections are not needed when an in-line viscometer is used and is located sufficiently close to the flowmeter.

The product of density and volume flow rate then yields the true mass flow rate of the fuel.

4.2 LHV Corrected Fuel Mass Flow Rate

In order to normalize engine performance data to a reference fuel heat content, a lower heating value correction (LHV_{cf}) may be applied to the true mass flow rate as in Equation 3.

$$LHV \text{ corrected mass flow rate} = \text{true mass flow rate} * LHV_{cf} * B_o \quad (\text{Eq. 3})$$

LHV_{cf} is defined as the ratio of measured LHV to a reference LHV. This correction is necessary because the LHV of fuel from different sources may vary significantly.

An additional correction for buoyancy (B_o) is also required when the true mass flow rate is corrected for the measured LHV of the fuel. When lower heating value measurements are made following any of the recommended test methods, the amount of fuel used is weighed "in air." However, fuel density, which is mass per unit volume, may or may not be referenced to "in vacuo" conditions. Therefore, a buoyancy adjustment (B_o) should be applied to ensure consistent reference to "in air" conditions for both LHV and fuel density, when density is referenced to "in vacuo" conditions.

NOTE: Fuel flow is also typically corrected to standard day conditions for pressure (δ) and temperature (θ^x), where the θ -exponent (x) is empirically determined by the engine manufacturer during development testing and corrects for the effect of different gaspath temperatures on specific heat. The reader should refer to ARP741 (2.1.1) for guidelines on making δ and θ corrections to fuel flow rate. Some thermodynamic performance models use LHV, θ and δ in the determination of the thermodynamic mass flow rate. Any discussion of such performance models is beyond the scope of this document. This document is only applicable to direct fuel flow measurements using turbine flowmeters.

4.3 Turbine Flowmeter Calibration and Corrections

The turbine flowmeter calibration process is critical in determining the volume flow rate during actual operation. The traditional representation of turbine flowmeter characteristics has been the K-factor curve illustrated in Figure 1. K-factor (cycles/US-gal or cycles/L) is shown as a function of flowmeter output frequency divided by kinematic viscosity (f/ν). The Universal Viscosity Curve (UVC) is a K-factor versus f/ν curve generated from calibration data of a particular flowmeter for fluids at several viscosities.

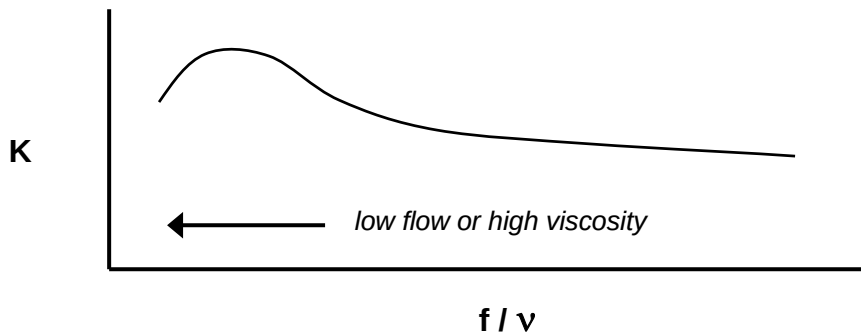


Figure 1 - K-factor calibration curve

Section 6.2 describes the use of two nondimensional parameters, Strouhal number (St) versus Roshko number (Ro), to quantify the flow characteristics of a turbine flowmeter. As will be explained in 6.2, the K-factor versus f/v plot (or, the UVC) is a special case of the correlation of the Strouhal number versus the Roshko number. The calibration curve is valid at the calibration conditions, and so appropriate temperature and pressure corrections must be made to account for the effect of actual operating conditions on turbine flowmeter geometry and kinematic viscosity.

In general, because of the nonlinearity of turbine flowmeter characteristics, the flowmeters should not be operated beyond the range of calibration, i.e., the characteristic plot should not be extrapolated. Even with all the corrections applied, special care should be exercised at low flow or high viscosity conditions, both of which correspond to low Ro number. The concept of the UVC, and of the St-Ro plot, gives an impression that a turbine flowmeter, calibrated at one viscosity, can be used at any other viscosity as long as the operating Ro number falls within the calibration range. However, the UVC and St-Ro plot have a break-away point as shown in Figure 2, which defines the lower limit of the “usable turn-down region,” for each viscosity (2.1.10). The break-away point can be determined from plots of calibration data at different viscosities.

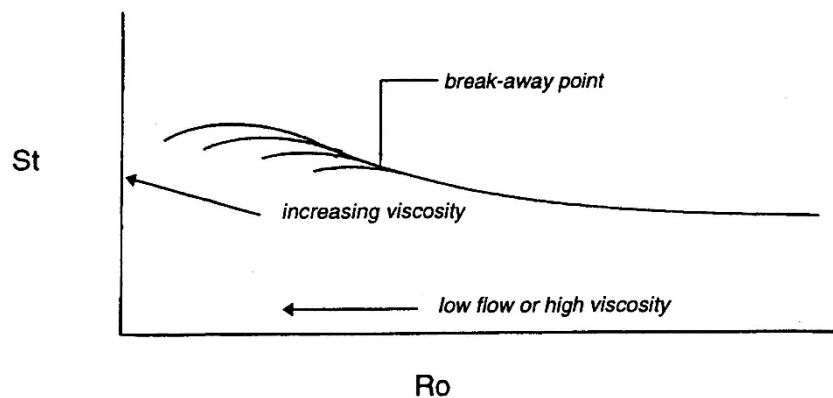


Figure 2 - Break-away point for a Strouhal-Roshko calibration curve

Use of a flowmeter below the break-away point, at viscosities and/or temperatures substantially different from those at which the meter was calibrated, can lead to serious errors in flow measurements.

4.4 Fuel Flow Calculation Summary

In general terms, the basis of calculating fuel flow is defined by Equation 2, where the true mass flow rate is equal to the product of fuel density and volume flow rate through the turbine flowmeter. After all the appropriate fuel properties are measured and corrected for pressure and temperature, Equation 4 can be used to calculate true mass flow rate ($W_{f,t}$).

$$W_{f,t} = 3600 * (f / K_{op}) * 8.345404 \text{ E-3} * (\rho_{ref} * VCF * C_{pfd}) \text{ lbm/h} \quad (\text{US}) \quad (\text{Eq. 4})$$

$$W_{f,t} = 3600 * (f / K_{op}) * 1.0 \text{ E-3} * (\rho_{ref} * VCF * C_{pfd}) \text{ kg/h} \quad (\text{SI})$$

Throughout this document, equations are provided in both US customary units (US) and SI units where appropriate. Appendix C contains the units conversion factors used. In both of the previous equations, 3600 is a time conversion of frequency, f , from Hz to cycles/h. In Equation 4 (US), 8.345404 E-3 is a density conversion of ρ_{ref} from kg/m^3 to lbm/US-gal yielding fuel mass flow rate in US customary units of lbm/h . In Equation 4 (SI), 1.0 E-3 is a density conversion of ρ_{ref} from kg/m^3 to kg/L yielding fuel flow rate in SI units of kg/h . Different units conversion factors may have to be used if the units of the measured parameters are different from those given in this document.

In order to normalize engine performance data to a reference fuel heat content, fuel flow rate is corrected both to a standard lower heating value (LHV_{cf} , 5.3) and for buoyancy effects (B_o , 5.4). Equation 5 can be used to calculate LHV corrected fuel mass flow rate ($W_{f,LHV}$).

$$W_{f,LHV} = W_{f,t} * \text{LHV}_{cf} * B_o \quad (\text{Eq. 5})$$

4.5 Document Summary

Section 5 describes the basis for each parameter in Equations 4 and 5 including procedures for the measurement of relative density, viscosity and lower heating value and the appropriate temperature and pressure corrections for relative density and viscosity.

Section 6 discusses turbine flowmeter calibration characteristics.

Section 7 recommends appropriate use of the fuel flow calculation process.

Table A1 of Appendix A lists the recommended ASTM and API measurement methods along with appropriate temperature and pressure correction methods for fuel properties in Table A2. The repeatability and reproducibility of the various test methods may be found in Table A3 of Appendix A for easy reference and comparison.

Finally, the sample calculation in Appendix B and the equations identified throughout this document are provided in both US customary and SI units to facilitate implementation of the recommended methodology.

5. FUEL PROPERTY MEASUREMENTS AND CORRECTIONS

5.1 Density

The density of a fuel sample is measured at a given temperature and pressure. During actual engine operation in flight or in a test cell environment, fuel passing through the turbine flowmeter may be at a significantly different temperature and/or pressure. Hence, it is not only necessary to measure the density of the fuel sample, but also to correct the measured value for the fuel temperature and pressure that exists during actual engine operation.

5.1.1 Density: Measurement

Fuel density can be measured using the following devices:

- a. Digital Density Meter: ASTM D4052 (2.1.3)
- b. Bingham Pycnometer: ASTM D1217 (2.1.3)
- c. Hydrometer: ASTM D1298 (2.1.3)

Both the digital density meter and pycnometer measure fuel sample density (ρ_{ref}) at the reference temperature ($T_{\text{ref}} = 60^\circ\text{F}$ or 15°C). The Bingham Pycnometer, although most accurate of the three, is however a much more labor intensive device. If an in-line digital density meter is placed sufficiently close to the flowmeter to measure fuel density at actual engine operating conditions, then the corrections for operating temperature and pressure discussed in the next two sections are not needed.

Both the hydrometer and the digital density meter can be used for measuring fluid relative density ($RD_{T_s/T_{\text{ref}}}$), formerly referred to as specific gravity in the literature. Relative density of the fuel sample is defined by Equation 6 (ASTM D1250, 2.1.3) as the ratio of the fuel sample density (ρ_s) at the sample temperature (T_s), to the density of water at the reference temperature (T_{ref}). When the relative density of the fuel sample is measured, it must be converted to density (ρ_s) using Equation 6.

$$RD_{T_s/T_{\text{ref}}} = \rho_s / \rho_{\text{water,ref}} \quad (\text{Eq. 6})$$

where:

$$\rho_{\text{water,60F}} = 999.012 \text{ kg/m}^3 \text{ in vacuo (ASTM D1250, 2.1.3)}$$

$$\rho_{\text{water,15C}} = 999.103 \text{ kg/m}^3 \text{ in vacuo (ASTM D1250, 2.1.3)}$$

When a borosilicate glass hydrometer is used to measure fuel sample relative density, a stem correction factor for hydrometer thermal expansion (HYC) shown in Equation 8 should be applied to the sample density (ρ_s) as in Equation 9. The stem correction in Equation 8 is applicable to borosilicate glass hydrometers. The corrected sample density ($\rho_{s,\text{HYC}}$) is then referenced to T_{ref} using the iterative procedure illustrated in Appendix B.3 to obtain ρ_{ref} .

$$\Delta T_s = T_s - T_{\text{ref}} \quad (\text{Eq. 7})$$

$$\begin{aligned} \text{HYC} &= 1 - (1.278 \text{ E-5} * \Delta T_s) - (6.2 \text{ E-9} * \Delta T_s^2) & (\text{US}) \\ &= 1 - (2.3 \text{ E-5} * \Delta T_s) - (2 \text{ E-8} * \Delta T_s^2) & (\text{SI}) \end{aligned} \quad (\text{Eq. 8})$$

$$\rho_{s,\text{HYC}} = \rho_s * \text{HYC} \quad (\text{Eq. 9})$$

The repeatability and reproducibility of each of the measurement methods discussed above is listed in Table A3 of Appendix A and allows users to quantify differences in measurement method results.

5.1.2 Density: Temperature Correction

If the fuel temperature at the flowmeter during engine operation is different from the reference temperature, then a correction is made to the sample density measurement (ρ_{ref}) to account for the effect of actual fuel operating temperature (T_{op}) on density. This correction is not necessary if an in-line digital density meter is used.