COMPARISON OF CORIOLIS AND TURBINE TYPE FLOW METERS FOR FUEL MEASUREMENT IN GAS TURBINE TESTING

J. D. MacLeod and W. Grabe
National Research Council
Ottawa, Ontario, Canada

ABSTRACT

The Machinery and Engine Technology (MET) Program of the National Research Council of Canada (NRCC) has established a program for the evaluation of sensors to measure gas turbine engine performance accurately. The precise measurement of fuel flow is an essential part of steady-state gas turbine performance assessment. Prompted by an international engine testing and information exchange program, and a mandate to improve all aspects of gas turbine performance evaluation, the MET Laboratory has critically examined two types of fuel flowmeters, Coriolis and turbine. The two flowmeter types are different in that the Coriolis flowmeter measures mass flow directly, while the turbine flowmeter measures volumetric flow, which must be converted to mass flow for conventional performance analysis. The direct measurement of mass flow, using a Coriolis flowmeter, has many advantages in field testing of gas turbines, because it reduces the risk of errors resulting from the conversion process. Turbine flowmeters, on the other hand, have been regarded as an industry standard because they are compact, rugged, reliable, and relatively inexpensive.

This paper describes the project objectives, the experimental installation, and the results of the comparison of the Coriolis and turbine type flowmeters in steady-state performance testing. Discussed are variations between the two types of flowmeters due to fuel characteristics, fuel handling equipment, acoustic and vibration interference and installation effects. Also included in this paper are estimations of measurement uncertainties for both types of flowmeters.

Results indicate that the agreement between Coriolis and turbine type flowmeters is good over the entire steady-state operating range of a typical gas turbine engine. In some cases the repeatability of the Coriolis flowmeter is better than the manufacturers specification. Even a significant variation in fuel density (10%), and viscosity (300%), did not appear to compromise the ability of the Coriolis flowmeter to match the performance of the turbine flowmeter.

INTRODUCTION

In the accurate assessment of gas turbine performance, the establishment of correct fuel flow is important. Fuel flow is considered as a performance parameter on its own merits, but it also appears in the much used specific fuel consumption function. Thus the measurement of fuel flow is critical to the certification of new engines and the acceptance testing of overhauled ones.

Largely prompted by the NRC's participation in the AGARD-sponsored Uniform Engine Testing Program, an examination of the measurement of fuel flow was initiated, with the purpose of improving accuracy and evaluating new methods of flow establishment. Although fuel flow, in aviation gas turbine testing, is evaluated in the form of mass flow, most measurements are being carried out using volume flowmeters, predominately of the turbine type (Grabe, 1988). Traditionally, NRC had been using turbine type flowmeters to measure fuel flow volumetrically, with appropriate conversion factors to calculate mass flow. Recently, interest in the direct measurement of mass flow, using Coriolis type flowmeters, has emerged from field testing of gas turbines, in a steady-state mode, where access to correct volume-mass conversion is not always available.

The Coriolis type flowmeters have been used for several years in the process industries to measure and control production of fluids and fluid/solid mixtures. The emphasis in this role was the necessity of a simple, reliable and robust instrument to measure flowrate independent of temperature, density, or viscosity.

The use of Coriolis flowmeters to measure fuel flowrate in gas turbine testing is relatively recent. The advantages are obvious, direct measurement of mass flow of fuel, simplicity, and low maintenance. The disadvantages include possibly higher pressure losses (depending on internal tube configuration) and high initial costs (Furness, 1991).
A limited comparison of the performance of turbine flowmeters and a Coriolis type flowmeter was undertaken by NRC to get a better understanding of both types of flow measurement devices. All tests were confined to steady-state operation.

PROJECT OBJECTIVES
The objectives of this flowmeter comparison project were:

a) to assess the strengths and weaknesses of both turbine and Coriolis flowmeters,
b) to evaluate the Coriolis flowmeter as to its suitability for use in gas turbine testing under steady-state laboratory conditions,
c) to comment on the suitability of the Coriolis flowmeter under field testing conditions,
d) the verification of accuracy claims of the Coriolis flowmeter,
e) to examine the calibration methodology for a mass flowmeter.

FUEL FLOW MEASUREMENT

Before comparing the performance of turbine and Coriolis type flowmeters, it is important to fully understand the principles under which each device operates. The limitations and strengths of each flowmeter type obviously have a strong bearing on the usefulness and accuracy of the test results obtainable in both laboratory and field testing conditions. Included in this segment of this paper are brief descriptions of the operating principles of both types of flowmeters.

Turbine Flowmeters
The turbine flowmeter, as a measuring device for liquid and gaseous flow, has been in use for a considerable time, and, hence, its principles are generally well-known among users. In brief, fluid flow is directed through a metering body with a finely-machined cylindrical duct, in which a turbine rotor is placed, in line with the flow. Disregarding small effects, the turbine rotates in direct proportion to the velocity of the fluid flow through the meter. A magnetic or modulated carrier pickup detects the passage of each rotor blade tip and generates a pulse. Because of geometric peculiarities and fluid effects, each flowmeter must be calibrated for accurate flow measurement. This is done by correlating the pickup pulses with either known volumes of flow passing through the meter and being collected and weighed or with known liquid mass flows passing through the meter and being collected and weighed subsequently. An in-depth treatment of turbine flowmeter systems has been given by Zimmermann and Deery (1977).

Since the turbine flowmeter is a volume flow measuring apparatus, whereas fuel mass flows are rather needed in gas turbine testing, conversion from volume to mass is required. To do so, certain fluid properties must be established, and their accuracies are directly reflected in the final accuracy of the mass flow. The equation for fuel mass flow may take the form:

$$W_f = \frac{FREQ \cdot 3.7816730 \cdot RD_f}{C_p \cdot K}$$  (1)

Where:
- $W_f$ = fuel flow corrected to standard conditions [kg/h or lbm/h]
- $FREQ$ = flowmeter frequency [pulses/s, Hertz]
- 3.7816730 = volume-mass conversion factor
- $RD_f$ = relative density (specific gravity) at fuel temperature
- $C_p$ = flowmeter thermal correction factor
- $K$ = flowmeter calibration factor [pulses/US gallon]

A similar expression can be written for flow units of lbm/h. Details of the flow equation derivation can be found in a report by Grabe (1988). It should be noted that the K-factor has the basic form "pulses per unit volume"; the unit "US gallon" has been carried over, in this instance, from the original one of the ballistic flow calibrator, in use at the National Research Council in Ottawa.

To facilitate data comparison between different test and fuel conditions, it is customary to reduce observed flow data to standard values:

$$W_f^* = \frac{W_f}{\delta} = \frac{NHCR}{NHCR}$$  (2)

Where:
- $W_f^*$ = fuel flow at test conditions [kg/h or lbm/h]
- $W_f$ = fuel flow corrected to standard conditions [kg/h or lbm/h]
- $\delta$ = (engine inlet total pressure)/(standard day barometric pressure)
- $\Theta$ = (engine inlet total temperature)/(standard day temperature)
- $NHCR$ = reference net heat of combustion [MJ/kg or BTU/lb]
- $NHCR$ = reference net heat of combustion [MJ/kg or BTU/lb]

The first part of the correction term yields a fuel mass flow corrected to standard day conditions, while the second part allows for variances in energy content in a certain fuel batch. In engine performance establishment, it is the energy input for a given thrust or power output which, ultimately, is of consequence.

Coriolis Flowmeters
A Coriolis mass flowmeter measures mass flow directly, using the Coriolis Principle, which is based on the conservation of angular momentum, as it applies to the Coriolis acceleration of a given fluid. In principle, a Coriolis mass flowmeter consists of a tube with a fixed inlet and outlet, which is vibrated sinusoidally from the axis formed by the inlet and outlet ends. The tube may be either straight or omega shaped, and is vibrated using a drive coil attached at the axis. Electromagnetic sensors are mounted upstream and downstream of the drive coil to measure velocity signals from the vibrating tube. This means that liquid flow is measured by transferring vibrational energy from the meter tubing to the flow liquid and back to the meter. To appreciate this principle, imagine a vibrating tube as shown in Figure 1. If no liquid is flowing, the drive coil in the middle of the tube will cause both arms to vibrate in phase. Mass flowing into the tube starts to receive vibrational energy from the tube walls as it enters the first bend (Figure 2). In this process, the tube loses the same amount of energy. The result is the phase of the vibrational cycle lags at the upstream sensor location; the reverse will happen at the downstream location. The liquid is vibrating as it enters the bend, but transfers this energy to the pipe. The result is that the mass flow advances the vibrational phase at the downstream sensor location. When combined, these two changes in vibrational phase produce a twisting of the flow tube as shown in Figure 3. The
amplitude of this twist is directly proportional to the mass flow rate and is nearly independent of the temperature, density, or viscosity of the liquid involved. In practical application, a Coriolis mass flowmeter may contain two parallel tubes, but the principle outlined remains unchanged.

While most of the effects of the above criteria on turbine meters are well documented (Grabe, 1988), the effects on the Coriolis meter are not.

To establish any installation effects on the Coriolis meter, the meter was installed in several configurations: fixed mounting, and flexible mounting. To analyze fuel temperature effects, tests were performed on different days with different inlet fuel temperatures.

For the investigation of relative density and viscosity effects, two fuel types were used, one 10% denser, and with 300% higher viscosity than the other. Noise and vibration effects were investigated by placing the Coriolis meter in close proximity to an afterburning turbofan engine producing noise levels up to 173 dB. Finally, the Coriolis meter was tested over a low and a high flow range using two different gas turbine engines. For low flow range testing (800-2400 lbm/hr) an Allison T56 turboprop engine was used, while for the high flow range (500-9000 lbm/hr), the flowmeter was measuring the core flow of a General Electric F404 afterburning turbofan engine.

**TEST SET-UP AND INSTRUMENTATION**

To compare the turbine and Coriolis flowmeters, the Coriolis meter was installed in series with two turbine meters in the fuel delivery system of a gas turbine engine. The evaluation procedures included observations of the installation and operation of the meters in general, and more specifically, a comparison of the flow measurements between the average of two turbine meters, and the Coriolis meter.

**Installation Criteria**

The test set-up was designed to evaluate the flowmeters under various conditions to establish the effects of the following criteria:

- a) installation,
- b) fuel temperature,
- c) relative density (specific gravity),
- d) viscosity,
- e) noise and vibration, and
- f) flow range.

Omnitrak Flow Calibrator

The Institute for Mechanical Engineering, National Research Council, is the custodian of an Omnitrak ballistic flow calibrator, Model OT-150, by Flow Technology, Inc. It calibrates a turbine flowmeter by correlating the pulses generated by its pick-off with a precise volume of fluid.

The Omnitrak ballistic calibrator incorporates a piston which travels inside a honed cylinder, pushing the calibration fluid along its path, and, further downstream, through the flowmeter to be calibrated. A piston rod is connected to the piston, carrying a photoelectric sensor. The sensor, or encoder, slides over a finely etched glass rule, generating pulses from the etched markings. These pulses have been, through previous calibration, correlated with a specific volume, hence, a precise calibration volume can be determined from the encoder pulses. This correlation between encoder pulses and volume forms the basis of the calibration constant of the calibrator, also referred to as the K-factor of the calibrator. As an indication of the fine resolution of the calibrator...
calibration, some 62,000 markings on the glass rule represent one US gallon.

A calibrator K-factor for the flowmeter is being calculated from primary data through the relationship:

\[ K = \frac{\text{No. FMP} \times \text{T VOL}}{\text{T FMP} \times \text{VOL}} \]  

Where:

- \( K \) = calibration factor of the flowmeter [pulses/US gallon] (or any other specified unit volume)
- \( \text{No. FMP} \) = number of flowmeter pulses collected [pulses]
- \( \text{T VOL} \) = time required for the test volume to be displaced [s]
- \( \text{T FMP} \) = time required for collecting the flowmeter pulses [s]
- \( \text{VOL} \) = volume of fluid displaced [US gallon or fraction thereof] (or any other specified unit volume)

A detailed description of the Omnitrak calibrator can be found in the manufacturer's manual (FTI 1982).

Since the calibration factor of the flowmeter is derived from the calibration constant of the calibrator, which is based on reference conditions, the K-factor must be corrected to the actual conditions, i.e. temperatures and pressures, prevailing at the time of calibration (Grabe 1991).

TEST RESULTS

Before a comparison between the turbine and Coriolis flowmeters could be made, it was necessary to establish the repeatability of the two turbine meters used as the reference for the low flow range and high flow range testing. Previous work (MacLeod and Orbanski, 1992) determined that the agreement between the two one-half inch turbine flowmeters used with the Allison T56 engine was ±0.16%. For the higher flow range, the agreement between the 3/4-inch and 1-inch turbine flowmeters of the General Electric F404 testing was ±0.2%, as shown in Figure 4.

Low Flow Range Testing

To evaluate the Coriolis mass flowmeter in the lower flow regime, the device was installed in series with existing turbine meters in the fuel delivery system of an Allison T56 turboshaft engine. The Coriolis mass flowmeter was installed in three different configurations. In the first one, the flow sensor was placed in the fuel line, half way between the engine fuel control and the facility turbine meters. Two lengths of approximately two metres of flexible fuel line connected the Coriolis flow sensor to the engine and the turbine meters upstream. The flexible hoses were attached directly to the flanges of the sensor unit. For the second set-up, the sensor was moved to a position one metre upstream of the turbine meters. In both configurations, the sensor was placed on a foam pad sitting on the concrete floor. For the final configuration, the Coriolis flow sensor was rigidly bolted to the floor as described in the installation manual (Schlumberger, 1991).

A total of 14 steady-state test runs were performed with the Coriolis mass flowmeter installed in the fuel system. As shown in Figure 5, the comparison between the turbine and Coriolis flowmeter is quite good, with 95% of the data falling within the ±0.3% scatter band, over the tested flow range. The fuel temperature did not appear to have any influence on the test results as indicated in Figure 6. This includes testing done with two different fuel types. The first fuel had a relative density of 0.763 and a viscosity of 1.194 centistokes at 15.56°C, while the second fuel had a relative density of 0.839 and a viscosity of 4.112 centistokes. As far as installation effects are concerned, there was no apparent correlation between the three configurations and the variation between the turbine and Coriolis meters, as can be seen from the plot against run numbers in Figure 7. Configuration two was an attempt to see if the pressure fluctuations at the fuel control inlet were propagating upstream and affecting the Coriolis sensor. This was found not to be the case. The sensor, placed less than two metres from the engine did not experience any fluctuations as a result of noise, vibration, or electrical interference. Noise levels near the sensor were approximately 125 dBA.
To evaluate the Coriolis mass flowmeter in the higher flow regime, the device was placed in series with existing turbine meters in the fuel delivery system of a General Electric F404 afterburning turbofan engine. The Coriolis mass flowmeter was installed in two different configurations. In the first, the flow sensor was placed in the fuel line, half way between the engine fuel control and the facility turbine meters, sitting loosely on the floor. Approximately two metres of flexible fuel line were between the engine and the Coriolis flow sensor and between the sensor and the turbine meters upstream. For the second set-up, the sensor was rigidly bolted to the floor as described in the installation manual (Schlumberger, 1991).

Six steady-state test runs were performed with the Coriolis mass flowmeter installed in the F404 fuel system. In Figure 8, the comparison between the turbine and Coriolis flowmeter indicates a divergence between the two fuel meter types of up to 1.2%, over the tested flow range. In every test, the Coriolis meter always read a higher value than the average of the two turbine meters.
Based on previous experience with Coriolis mass flowmeters (MacLeod, 1987) the sensitivity of the Coriolis flow tubes to noise and vibration is significant. In the tests discussed here, the effects of loose versus solid mounting were measurable. The divergence in the flowrate of the two meter types is speculated to be the result of airborne noise vibrating the Coriolis meter tubes. These vibrations would cause higher tube oscillations, indicating higher of airborne noise vibrating the Coriolis meter tubes. These vibrations in the flowrate of the two meter types is speculated to be the result and vibration is significant. In the tests discussed here, the effects of the acoustic energy in the test cell also is increasing with engine power. Unfortunately, time constraints did not permit testing with an acoustic enclosure surrounding the Coriolis meter to verify this hypothesis.

Coriolis Meter Calibration

Any flowmeter has to be checked for its calibration, at the beginning of its service life and periodically thereafter. The calibration of turbine flowmeters is well-established and documented. The calibration technique for mass flowmeters of the Coriolis type, with a ballistic calibrator, is less known, simply because these meters have only recently come into wide-spread use. It has been said that the accuracy of a Coriolis mass flowmeter is inherently superior to that of a ballistic calibrator, and, hence, a calibration by that apparatus would be meaningless. However, until that proposition has been proven valid, a technique has been developed at NRC by which mass flowmeters can be calibrated.

The mass flowmeter has a frequency output, in addition to a voltage one, which is proportional to the flowrate. Thus, the meter can be treated like a turbine flowmeter in a ballistic calibrator, with the output parameters being valid entities, viz. volume flowrate and K-factor. The frequency, calculated in turbine flowmeter calibration, becomes now an input parameter. To obtain a mass flow calibration, however, some further steps are required. A mass flow has to be computed by the equation:

\[ m = \dot{V} \times RD \times 3.7816730 \quad [kg/min] \quad (4) \]

Where:
- \( m \) = mass flow at the fluid temperature [kg/min]
- \( \dot{V} \) = volume flow rate through the meter [US gallon/min]
- \( RD \) = relative density of calibration fluid at fluid temperature 3.7816730 = volume-mass conversion [kg H_2O @15.56°C/US gallon]

Knowing the mass flowrate of a calibration point, one can calculate a modified K-factor for the meter in terms of "pulses per kg", instead of "pulses per US gallon" by:

\[ K_m = \frac{FREQ \times 60}{m} \quad \text{[pulses/kg]} \quad (5) \]

The question remains how to evaluate best the calibration. Two possibilities have been examined. One, the most logical one, has the mass flow plotted against frequency, on the basis that a direct proportionality supposedly exists between them. The other has the modified K-factor, \( K_m \), plotted against frequency. Since viscosity is said not to affect the flow measurement of a Coriolis meter, frequency does not have to be corrected for its effects. Examination of the two approaches shows that the latter one is superior in that it produces a far better resolution, and, hence, more accurate calibration evaluation. As an example, in one particular mass flowmeter calibration it was found that differences, between distinct calibration points and values obtained from curves, varied from 0.1% to 1.2% for the \( K_m \) approach and 0.1% to 4.5% for the straight mass flow one. The differences increased from high to low flows. This observation leads to the conclusion that, on account of the better resolution of its plotting scale, the calibration evaluation via the modified K-factor yields more accurate results and should be preferred.

UNCERTAINTY ANALYSIS

Flow Measurement by Turbine Flowmeter

The uncertainty analysis of fuel flow measurement is rather complex and depends on many small contributors. An attempt has been made by Grabe (1988) to give a detailed error analysis of the whole fuel flow measuring system, which uses a turbine flowmeter. It was shown that the possible error depends, to a large degree, on the conditions under which the measurements are taken. In that analysis, two conditions were chosen: one severe the other average. The severe condition, for example, would consider extreme fluid temperatures, low flow rates, which means a low meter frequency, and a method of relative density determination with a high reproducibility uncertainty. The average conditions were those more likely to be encountered in the field.

The contributing elements of an uncertainty analysis of observed fuel flow include such items as the turbine flowmeter frequency, the fluid relative density, the correction for flowmeter thermal expansion, and the K-factor, see equation 1. For the corrected fuel flow, inlet temperatures and pressures, as well as the fuel net heat of combustion, further add to the final uncertainty. Each of these items depend, in turn, on contributing elements of their own. For example, relative density, formerly called specific gravity, at measurement temperature, is a function of its relative density at reference temperature, the fuel temperature, and the fuel’s critical temperature. The uncertainty of each of these contributors is created during measurement.

Taking all of these possible error contributions into account, it was found that, in a well-run system, where great care is taken at all steps in the chain, the following uncertainties may occur. The observed fuel flow, under average measurement conditions, could be expected to have an overall uncertainty of ±0.4%. Under severe conditions, this uncertainty would nearly double to ±0.7%. For corrected fuel flow, including corrections for the fuel net heat of combustion, the uncertainty would be ±0.65% for average conditions and ±1.0% for severe ones.

It must be borne in mind that these uncertainties are by no means guaranteed. Only if careful steps are taken along the fuel flow establishment path, can these rather tight uncertainties be achieved. Each element contributes, in some way, to the final accuracy of the fuel flow establishment. For example, if an average K-factor were used for the whole flow range, instead of following the universal curve for accurate local values, the K-factor error contribution could amount to 0.5%, rather than a predicted 0.2% from the analysis (Grabe 1988).
Flow Measurement by Coriolis Flowmeter

The contributing elements of an uncertainty analysis of observed fuel flow for a Coriolis flowmeter include such items as the drive coil frequency, the frequency response of the electromagnetic sensors, the thermal correction for flowmeter tube elasticity changes, zero stability, and the K-factor. For the corrected fuel flow, inlet temperatures and pressures, and the fuel net heat of combustion, must be considered to determine the final uncertainty. Each of these items depend, in turn, on contributing elements of their own.

Taking all of these possible error contributions into account, it was found that the following uncertainties may occur. The observed fuel flow, under average measurement conditions, could be expected to have an uncertainty of ±0.15% of reading ± zero stability. The zero stability can be as high as ±0.5% of reading based on the test results shown here and in previously published work (Keita, 1989).

SUMMARY AND CONCLUSIONS

For accurate fuel flow measurement, certain precautions must be taken in installing and operating a flowmeter, be it a turbine or a Coriolis type device. The turbine flowmeter is a relatively simple device measuring volumetric flowrate, which is affected by fuel temperature, relative density, and viscosity of the fluid. The Coriolis mass flowmeter indicates mass flow directly through a reasonably complex procedure, with little or no influence from the properties of the fluid.

Comparison tests between the turbine and Coriolis flowmeters indicated good agreement of about ±0.3% over the lower portion of the flow range of the Coriolis meter examined. At higher flowrates, the Coriolis flowmeter indicated flowrates approximately 0.5% higher than the two turbine meters in series with it. This divergence was attributed to noise and vibration emanating from the gas turbine. Fuel temperature, relative density or viscosity did not appear to influence the Coriolis flowmeter in any way. Installation effects on the Coriolis flowmeter were minimal, and the pressure losses were similar to that for the turbine flowmeters (depending on turbine meter diameter). Drifting in the electronic components of the Coriolis flowmeter required frequent adjustments of the frequency board to maintain close agreement with turbine flowmeter results. If undetected and uncorrected, these drifts could lead to substantial measurement errors.

RECOMMENDATIONS

Based on previous experience with Coriolis mass flowmeters (MacLeod, 1987) and the results of this study, the Coriolis flowmeter has shown to have the capability of measuring accurately fuel flow to a gas turbine, provided certain precautions are observed. It is recommended that Coriolis flowmeter be seriously considered for gas turbine testing, both in the laboratory and in field installations. However, because of the complexity of the electronic conditioning required to monitor the Coriolis flowmeter, the device should, for the time being, be used in series with a turbine flowmeter to detect any possible drift in the Coriolis meter readings.

REFERENCES


