White Paper

ADAPTIVE CONSUMPTION MEASUREMENT: UNDERSTANDING AND ELIMINATING COMMON MARINE FUEL CONSUMPTION MEASUREMENT ERRORS

BY TAYLOR SCOTT, MICRO MOTION, INC.

Introduction

Understanding and optimizing fuel consumption of high horsepower engines is a growing trend among operators of any fleet size. Finding ways to increase efficiencies and balance fuel inventories is paramount in today's competitive marine industry. In order to evaluate fuel consumption metrics, an operator must search for the appropriate equipment that enables their understanding of how much fuel each engine consumes. Process conditions, operating schemes, accuracy, turndown, and installation complexity should all be taken into account when purchasing such equipment and undertaking a fuel efficiency study with the ultimate goal of saving money.

Accurate fuel consumption measurements are the foundation for understanding operating efficiencies, which leads to more informed decision making across a vessel or fleet. The adoption of Coriolis flow meters is increasingly prevalent in the maritime industry because they offer solutions to challenges associated with volumetric measurements of heavy fuel oil (HFO) and marine gas oil. This paper describes some of the complex challenges of a marine fuel consumption measurement, and the advantages of Emerson's Marine Adaptive Consumption Measurement (ACM) over incumbent methods of a fuel consumption (FC) measurement.

Application

Some marine fuel systems require fuel be recirculated throughout the system, meaning all of the fuel sent to the consumer is returned to the flow loop.

Fuel consumption rate can be defined as the amount of fuel used by a consumer (i.e. main engine, generator, boiler, etc.) per unit time. A consumer's FC rate is calculated by comparing the measured rate of fuel that enters the consumer (supply) to the rate of fuel that exits (return), seen below in Figure 1.

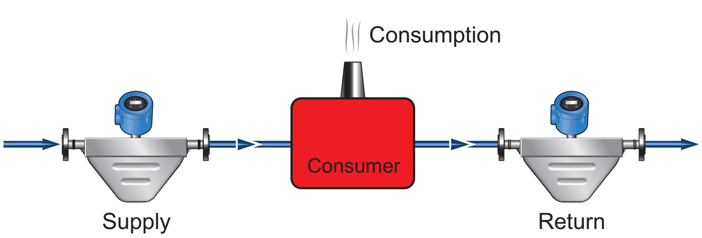

Figure 1. Using Two Coriolis Mass Flow Meters to Measure FC Rate

An engine's FC total by mass, $m_{consumption}$, is related to the supply flow total, m_{supply}, and the return flow total, m_{return}, as seen below in Equation 1.

Equation 1: $$m_{consumption} = m_{supply} - m_{return}$$

Coriolis meters report a variety of variables by directly measuring fuel mass flow, density, and temperature. FC mass and volume totals are calculated within the meter set itself.

Challenge

A FC measurement is difficult to make accurately due to a number of varying process conditions that force traditional measurement methods to be inaccurate and prone to errors.

Tank sounding measurements are used to determine the amount of fuel removed from a tank during the operation of a consumer. The measured change in depth is multiplied by a factor derived from the onboard tank calibration table to calculate a volume measurement. Sounding measurements are subject to errors associated with the assumptions made by the tank calibration table, which is generally derived from a theoretical calculation of the tank's dimensions. The tank sounding measurement can be reasonably accurate if taken correctly, however, factors such as trim, stratification, and temperature differences introduce error and uncertainty into the measurement process. Often, corrections are applied to mitigate these errors, however, the uncertainty of the corrections are often unknown and untraceable.

Volumetric flow meters can also be used to determine the rate at which fuel is consumed. While volumetric flow meters can provide relatively good data, they require assumptions to be made about the fuel properties (e.g., density) and also measurements of the process conditions (e.g., temperature and pressure). Combined, these factors can easily add uncertainties of up to more than 1% of the final corrected volume measurement.

Volumetric flow meters often measure flow based upon an operating principal of moving parts that tend to wear, corrode, and are prone to frequent maintenance. Some volumetric flow meters require flow conditioners or straight pipe runs before and after the point of measurement.

Conversions to mass of both volumetric meter and tank sounding measurements introduces even more errors to FC reporting by neglecting stratification and temperature zone differences within a fuel tank or across a consumer.These measurements are further subject to errors from conversion table uncertainties, equipment conditions, and human interactions.

Even when used appropriately under ideal conditions, all measurement devices have some inherent random uncertainty. These intrinsic errors can cause measurement devices to report slightly different values even when adjacent, in-series and operating without flow diversion between them (i.e. fuel consumption). Therefore, it is possible for Supply and Return meters to report a non-zero differential measurement during periods of 100% recirculation when no fuel is being consumed, as highlighted below in Figure 2. This bias between a Supply and Return meter pair can apply to all FC measurement methods and will affect the accuracy of FC measurements made during periods of fuel consumption.

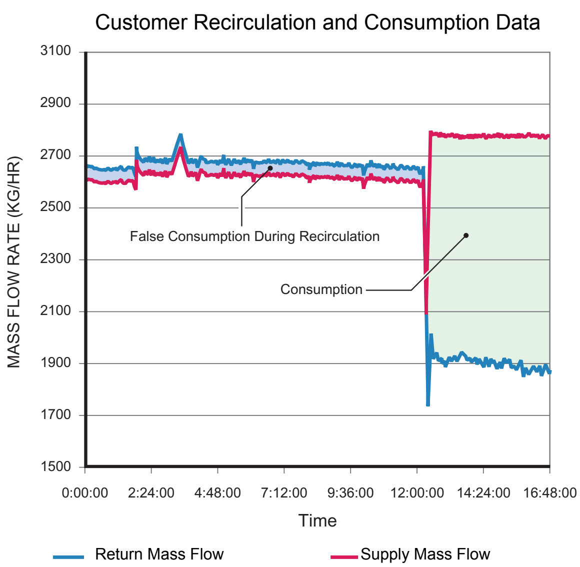

Figure 2. Discrepancies in Supply and Return Mass Flow Rates During Periods of Recirculation

At low FC rates, the accuracy specification of a FC measurement is affected by the combined system component accuracy specifications. When a relatively small differential flow value is calculated based upon a meter pair in series, the accuracy specification of the differential quantity increases.The accuracy limit of a differential measurement from a meter pair in series relative to the true value, E_{System}, can be expressed as a function of each meter's published accuracy specification, E_{Supply} and E_{Return}, and the Supply and Return mass flow rates, $\dot{m}_{Supply}$ and $\dot{m}_{Return}$ respectively, seen below in Equation 2.

Equation 2:

$$E_{System} = \frac{(E_{Supply} * \dot{m}_{Supply}) + (E_{Return} * \dot{m}_{Return})}{\dot{m}_{Supply} - \dot{m}_{Return}}$$

Fuel Consumption Percentage, FC%, can be expressed as a function of Supply mass flow rate, $\dot{m}_{Supply}$, and Return mass flow rate, $\dot{m}_{Return}$, seen below in Equation 3.

Equation 3:

$$FC\% = \frac{\dot{m}_{Return} * 100}{\dot{m}_{Supply} + \dot{m}_{Return}}$$

By normalizing the Supply and Return mass flow rates and assuming equal accuracy limits for a Supply and Return meter pair, Equation 2 can be rewritten as a function of FC percentage, FC%, seen below in Equation 4.

Equation 4:

$$E_{System} = E_{System'Return} * [2/FC\% -1]$$

A graphical representation of the accuracy limits of a differential measurement calculation is represented below in Figure 3.

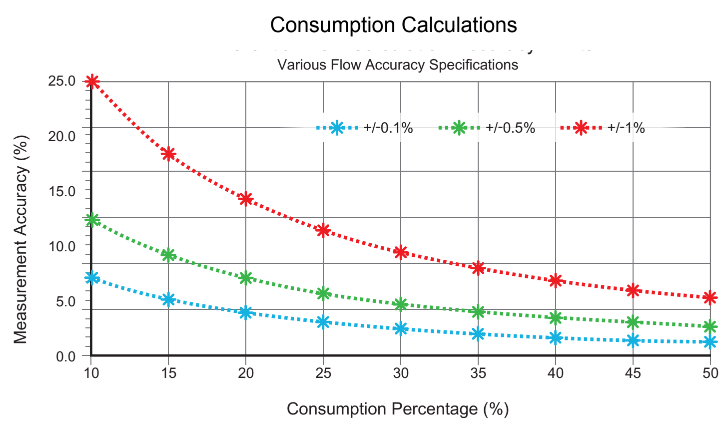

Figure 3. Differential Measurement Accuracy Limits for Meters in Series at Varying Consumption Percentages

Flow meters with improved accuracy specifications exhibit a distinct advantage when a differential measurement is required. With all types of flow meters, greater FC measurement errors are expected when relatively small differential measurements are made.

Unless these types of errors are adequately accounted for, all FC reporting methods, including fuel management software systems, will miscalculate FC rates and totals. These measurement discrepancies can force vessel operators to make uninformed operational decisions that adversely affect their inventory management, efficiency metrics, and financial bottom-line.

Solution

Emerson's Adaptive Consumption Measurement (ACM) feature mitigates common differential measurement errors by internally calculating a set of proprietary process variables based upon live data from a Supply and Return meter pair. This proprietary measurement allows a vessel to establish a FC baseline more accurately than with other volumetric or mass flow meters, tank sounding comparisons, or on-board fuel management computers.

The ACM feature simplifies fuel management by calculating and reporting a differential flow total equal to the amount of fuel consumed, eliminating the need to perform external calculations. This differential flow total eliminates the need to perform any tank measurements or to apply any conversion factors.

A digital communication link between a Supply and Return meter, as seen in Figure 4, allows the ACM system to reduce signal processing errors and measurement errors unique to a specific vessel by monitoring live meter performance, calculating proprietary differential process variables, and applying internal adjustments to meter specifications.

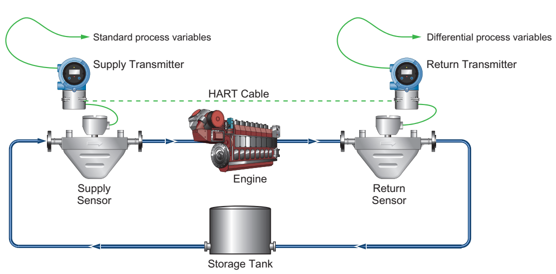

Figure 4. Digital Communication Link Between Supply and Return Meters

Every time a vessel recirculates fuel, the ACM feature calculates and stores a new type of flow measurement offset, or zero, unique to live process conditions. This Automatic Differential Zero corrects the natural bias created by temperature differences and combined meter tolerances in order to provide vessel operators with a more accurate FC measurement.

With the ACM feature enabled, a proprietary differential cutoff value is also automatically calculated within the meter system in order to limit the effects of process noise and sampling errors on a FC measurement.

This proprietary software does not affect the absolute measurement accuracy of the meters, but improves the differential measurement accuracy in challenging scenarios such as relatively small levels of fuel consumption.

Emerson's Adaptive Consumption Measurement feature minimizes false consumption data reporting and provides vessel operators and owners with more accurate FC information and overall measurement confidence.

Software Validation

A test stand designed to simulate a marine FC loop, represented by Figure 5 below, demonstrates the effectiveness of the ACM feature.

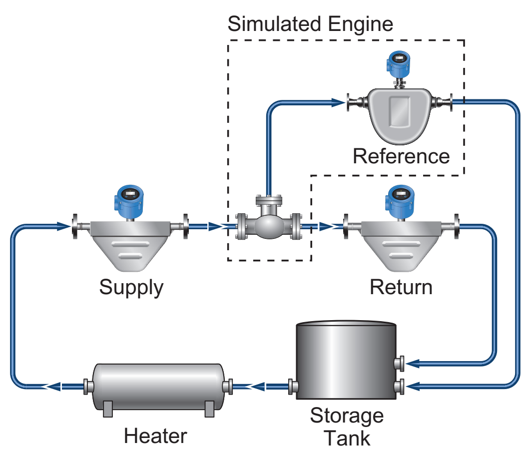

Figure 5. Marine Vessel Fuel Consumption Test Stand Flow Loop

Water, simulating fuel, leaves the Storage Tank, passes through the heater, and is measured by the Supply meter. Downstream of the Supply meter, a 3-way valve diverts a portion of the Supply flow stream into a Reference meter, and the rest through the Return meter before returning to the Storage Tank. The amount of water 'consumed', or diverted by the 3-way valve, is directly measured with a highly calibrated Reference meter. This reference measurement provides a baseline, accurate to ± 0.01 kg/hr, for comparing experimental FC measurements calculated with a Supply and Return meter.

For each trial, data for three different FC methods are simultaneously recorded for statistical comparison.

The first FC measurement examined is read directly through Emerson's proprietary ACM Modbus register, providing a simplified differential mass flow total for each trial.

The second FC measurement method examined is externally calculated by subtracting the Return meter's mass flow total from that of the Supply meter, as shown below in Equation 5. This method represents a typical Coriolis fuel consumption measurement method.

Equation 5: $m_{NoACM} = m_{Supply} - m_{Return}$

The third FC measurement method examined is calculated using the volume total, automatically calculated by the Coriolis meter, and a fixed density assumption about water at the experimental temperature, seen below in Equation 6, where Vcoriolis is the volumetric total measured by the Coriolis meter and ρWater, 70 °C is the density assumption of water at 70 °C.

Equation 6: $m_{vol} = V_{Coriolis} * \rho_{Water,70C}$

This method is represents the conversion of a perceived volume based upon a constant density assumption (i.e. tank sounding practices). This experimental calculation conservatively approximates errors from tank sounding as volumetric totals measured by Coriolis meters are calculated with directly measured density and mass.

Each FC trial is conducted with water at 70 °C and a Supply mass flow rate of 700 kg/hr. Each trial begins with a 15 minute period of recirculation during which Emerson's proprietary differential variables are automatically calculated and stored, followed by 20 minute periods at each of three different fuel consumption rates: 20%, 30%, and 40%. Multiple FC rates are tested by diverting the prescribed portion of the Supply flow rate into the Reference meter.

For each FC percentage, 15 trial measurement cycles are analyzed to validate the statistical significance of the experimental results. The Supply and Return meters are zeroed at 30 °C, to reproduce the practice of commissioning a vessel's meter system while in port. The Reference meter is zeroed at 70 °C to provide a more accurate baseline condition for comparison.

The percent error of each trial was determined for the FC data collected without and with the ACM enabled, seen below in Equation 6 and Equation 7 respectively, where m_{NoACM} and m_{ACM} represents the FC measurement made without or with the ACM enabled and $m_{Reference}$ represents the true FC value measured by the calibrated Reference meter.

Equation 7:

$$\%Error_{NoACM} = \frac{m_{NoACM} - m_{Reference} * 100}{m_{Reference}}$$

Equation 8:

$$\%Error_{ACM} = \frac{m_{ACM} - m_{Reference} * 100}{m_{Reference}}$$

The meters' published accuracy specifications, in addition to system calculation uncertainties, are used to calculate the total uncertainty of the FC measurements with and without the ACM application enabled, seen below in Equation 8 and Equation 9 respectively, where δ is each meter's uncertainty, Reference is the consumption total, σ is the standard deviation and N is the sample size.

Equation 9:

$$\partial Error_{ACM} = \sqrt{\left(\frac{\partial ACM}{Reference}\right)^2 + \left(\frac{\partial Reference * ACM}{Reference^2}\right)^2} + \frac{\sigma}{N}$$

Equation 10:

$$\partial Error_{No\,ACM} = \sqrt{\left(\frac{\partial Supply}{Reference}\right)^2 + \left(\frac{\partial Return}{Reference}\right)^2 + \left(\frac{\partial Reference * (Supply - Return)}{Reference^2}\right)^2} + \frac{\sigma}{N}$$

Test Results

The percent errors of all FC data collected is seen below in Figure 6.

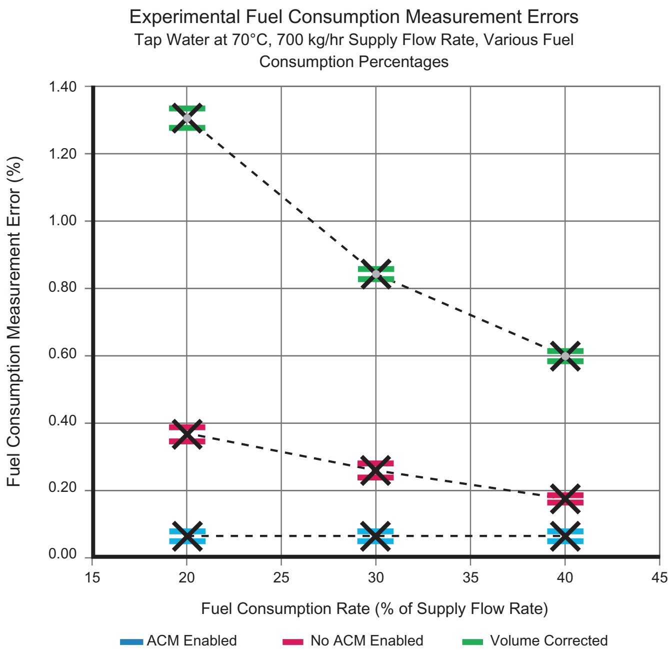

Figure 6. Fuel Consumption Measurement Errors

Based upon a complete uncertainty analysis and 95% confidence interval calculation, Emerson's ACM exhibits a statistically significant improvement in measurement accuracy when compared to measurements made without the software enabled.

The average errors and associated uncertainties in FC measurement accuracy at the previously described process conditions are seen below in Table 1.

Fuel Consumption (%)	ACM Error (%)	No ACM Error (%)	Volume Corrected Error (%)	ACM Advantage (Over No ACM)
20	0.07 ± 0.01	0.36 ± 0.03	1.29 ± 0.04	> 5 - 15x
30	0.07 ± 0.01	0.25 ± 0.02	0.84 ± 0.02	> 3 - 9x
40	0.06 ± 0.02	0.17 ± 0.02	0.58 ± 0.02	> 2 - 6x

Table 1: Improvement in Fuel Consumption Measurement Accuracy Achieved with ACM Enabled

As seen above in Figure 5 and in Table 1, Emerson's Adaptive Consumption Measurement feature offers a greater accuracy advantage at lower FC rates, where relatively high system accuracy errors exist. Overall, Emerson's ACM exhibits statistically significant improvements in accuracy compared to fuel consumption measurements made without the software enabled.

Conclusion

The adoption of Coriolis flow meters is increasingly prevalent in many different applications in the maritime industry because they offer solutions to challenges associated with volumetric measurements of heavy fuel oil (HFO) and marine gas oil. Based upon the results obtained in this validation test, the Emerson Adaptive Consumption Measurement feature improved the accuracy of a fuel consumption measurement up to 500% under laboratory conditions.

Improved fuel consumption data can be directly correlated to improved operational efficiencies. Access to this data allows a vessel operator and owner to better understand how operating procedure adjustments directly contribute to decreased costs. Increased measurement accuracy results in more responsive data and provides an operator with the ability to make decisions faster, improve their distribution of resources, and improve a vessel's operational efficiencies – ultimately leading to dramatic fleet-wide savings.

About Micro Motion

For over 35 years, Emerson's Micro Motion has been a technology leader delivering the most precise flow, density and concentration measurement devices for fiscal applications, process control and process monitoring. Our passion for solving flow and density measurement challenges is proven through the highly accurate and unbeatable performance of our devices.

Emerson Process Management
Micro Motion
7070 Winchester Circle
Boulder, Colorado USA 80301
T: +1 800 522 6277
T: +1 (303) 527 5200
F: +1 (303) 530 8459
www.MicroMotion.com

WP-002016 Rev A

EMERSON Process Management