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Liquid Flow Rate Automation & Uncertainty – Staying Drier

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Abstract **-** Real-life example of laboratory automation of data collection, device calibration, measurement uncertainty calculations & certificates for Liquid Mass Flow and Volumetric Flow Rate. Wet suits are not required to evaluate and compare coriolis mass flow meters and turbine volumetric flow meters in re-circulating systems and weigh standards. The effects of time, temperature, density, viscosity, air-buoyancy, flow stability, EMI and others can be startling; who knew? An off-the-shelf liquid recirculating system with data collection is evaluated with transfer standards for liquid flow rate and temperature. The flow system with turbine volumetric flow meters is compared with coriolis mass flow meter transfer standards. Various measurement agreements and errors are revealed for flow rate, temperature & density. Automation saves time, decreases measurement uncertainty and makes some flow rate analysis practical.

I. Topics of Interest

Automation, Mass, Force & Flow.

II. Introduction

The task is to reduce measurement errors and increase the amount of data that can be measured simultaneously in a production calibration environment while maintaining traceability to the National Measurement Institute. Hundreds of sensors must be calibrated daily to support several industries: semiconductor component fabrication, robotic welding, human body scanning, package scanning, metal cutting, silicon material fabrication, chemical mixing and thermal mass transfer to mention but a few. Calibration errors can injure or kill people and cost industry billions of dollars. Problems relating to calibration errors can be traced back a few thousand years by historians. Previous important work on calibration automation is focused in single and low volume calibration environments or a single measurement system in National Measurement Institutes (NMIs) or Nationally-recognized laboratories. This paper compares different measurement systems supporting full traceability to National Measurement Institutes (NMIs) in the U.S.A. and Germany and describes various measurement errors in the systems and sensors that were discovered in flow rates from 0.151 Liters Per Minute (LPM) to 33.38 LPM using sensors with classifications ranging from Traceability Group A1 through Traceability Group F as described in ISO 11631 (Measurement of fluid flow – Methods of specifying flowmeter performance).

III. Approach to the problem

Automate existing manual method of evaluating flow stands: collect, record, and retain calibration data in SI Units and lb-ft units (for legacy systems in the U.S.A.). Use coriolis meter transfer standards to evaluate recirculating flow systems employing turbine meter flow rate references. Automate Flow Dump Weigh Standard Method (direct pumping weigh method) to verify recirculating systems in a more efficient and effective manner. Automate constant level head tank supplied weigh standards as “in-house” check method and evaluation apparatus for coriolis flow rate masters. Participate in round-robin flow sensor evaluation with other flow laboratories monitored by NMI or 3rd party proficiency test house. Work with flow sensor manufacturers and NMIs to characterize all measurement uncertainty error sources of flow rate reference sensors used in recirculating flow systems in effort to establish flow stand calibration traceability.

A. Recirculating system for high volume calibrations

A recirculating flow system allows high volume calibrations because the fluid used in the calibration process is recycled through the feed tank reservoir during the calibration. Other types of calibration systems require a wait time for the fluid used in the calibration process to be pumped back to a reservoir and the reservoir to stabilize. With a recirculating flow system, transfer standards can be placed in line and software can be developed to guide operators to calibrate units with specific flow rate points while the software automatically collects and stores calibration data and prints calibration certificates. The recirculating system pumps fluid through horizontally-mounted flow references and the sensor-under-test as configured in Figure 1 (drawn with a coriolis transfer standard in the sensor-under-test position).

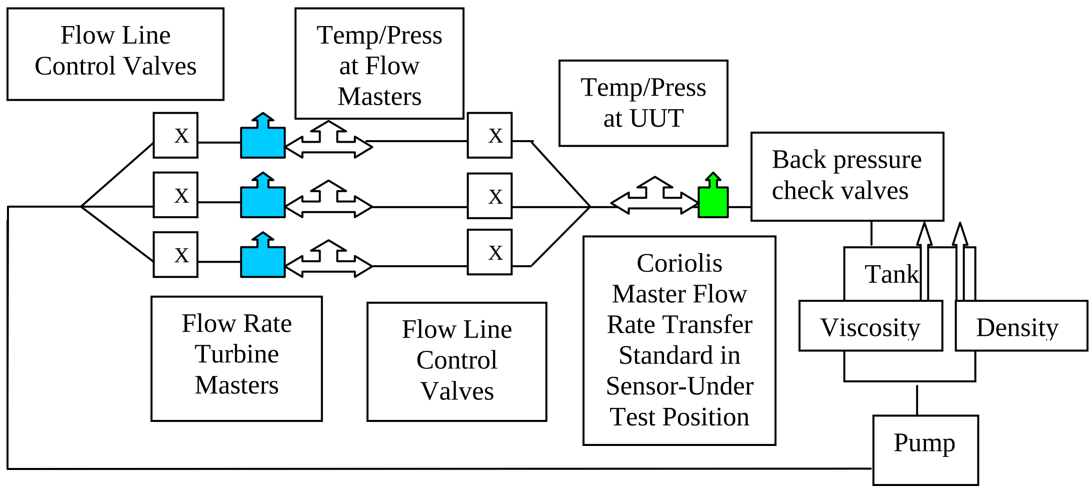

Figure 1. Simple Recirculating System with Coriolis Mass Flow Transfer Standard

The recirculating system was evaluated using a Flow Dump Weigh Standard (Figure 2). A timer-controlled diverter valve with an adjustable output was inserted in the Sensor-Under-Test Position. To minimize error, the diverter valve output flow to collection vessel must match the flow in the recirculating system.

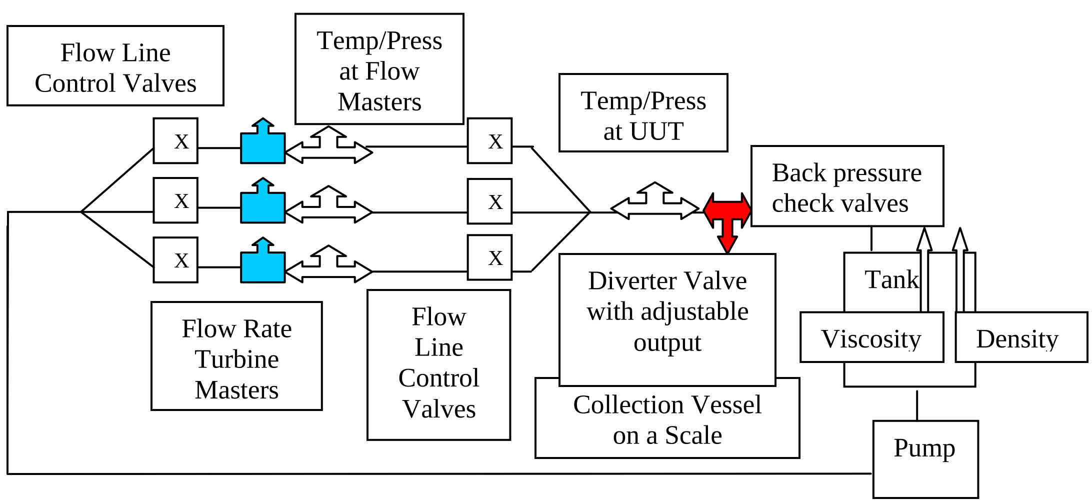

Figure 2. Simple Recirculating System with Flow Dump Weigh Standard

B. What turbine and coriolis meters measure and the influences of temperature and cavitation

Turbine meters are volumetric measuring instruments sensitive to viscosity changes – fluid speedometers with one or two rotors spinning from the velocity of fluid flow passing by the rotor(s). Coriolis meters are mass flow measuring instruments sensitive to density changes – fluid scales with an inner tube distorting from the mass of fluid flowing in the tube. Temperature influences the spacing of the fluid molecules which changes the viscosity and density of a fluid. Cavitation makes a fluid non-homogeneous for viscosity and density because cavitation affects the spacing of fluid molecules by introducing gas into the fluid or separating the fluid.

C. Turbine meter temperature compensation equation

$$Volumeric\_Flow\_Rate = GPM = \frac{\left[R_o * K_v * 60 * \left(1 + 28.8 * 10^{-6} * (T - 70)\right)\right]}{\left[S_t * \left(1 + 19.2 * 10^{-6} * (T - 70)\right)\right]} \qquad (1)$$

The off-the-shelf system turbine meter temperature compensation equation uses non-SI Units:

- GPM is Gallons Per Minute (1 gallon = 3.7854 * liter)
- S_t is the Strouhal coefficient (K-factor/Reynolds Number)
- R_o is the Roshko coefficient
- K_v is Kinematic Viscosity in centistokes (1 centistokes = 0.01 cm²/second)
- T is temperature in degrees Fahrenheit (degrees F = (1.8 * degrees Celsius) + 32)

The off-the-shelf system can report in SI Units.

D. External laboratory evaluations of turbine and coriolis meters

Two accredited laboratories evaluated the meters. The turbine meters were evaluated on piston-driven volumetric flow stands with 0.05% uncertainty by a laboratory NVLAP accredited for liquid flow rate. The coriolis meters were evaluated on volumetric rigs with 0.05% expanded uncertainty by a laboratory ILAC accredited for liquid flow rate.

E. Internal evaluation of mass flow rate, density and temperature

The coriolis meter mass flow rates were evaluated on in-house static weighing standards with 0.15% expanded uncertainty. The density calculations of the coriolis meters and turbine meter system were compared with density measured using standard 100ml cup and scale with 0.0014% expanded uncertainty. The temperature measurements of the coriolis meters and turbine meter system were compared using a temperature standard with 0.012% expanded uncertainty. Densities measured by the coriolis meters and the scale were compared with three Internet water-density calculation websites employing the U.S.A. NIST-water density equation.

F. Constant level head tank – static weighing standards for reference

A constant level head tank supply static weighing method is used for coriolis meter evaluation. Per ISO 4185 page 10, the mass flow is calculated using the equation:

$$Mass\_Flow\_Rate = q_m = 1{,}00106 * \left({m_1 - m_0}/{t} \right) \qquad (2)$$

Volumetric flow is calculated using the equation:

$$Volumetric\_Flow\_Rate = q_v = {q_m}/{Q} = 1{,}00106 * \left({m_1 - m_0}/{Qt} \right) \qquad (3)$$

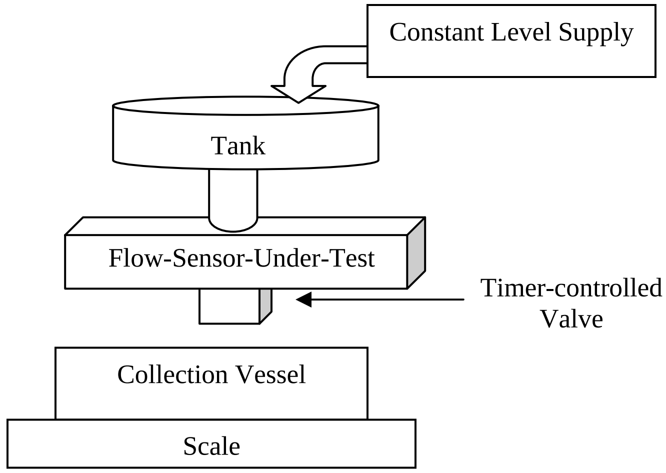

Figure 3. Simple Constant Level Head Stand

The simple constant level head stand (Figure 3) shows how the fluid passes through the flow-sensor-under-test to a collection vessel on a scale. The mass of the fluid is determined by double-weighing (mass of vessel prior to timed dispense subtracted from the mass of the vessel with fluid sample after the timed dispense). The valve was evaluated with ISO 4185 and ISO 9368-1 methods.

G. Equipment, accredited calibration laboratories and countries involved

The scales are calibrated on site by an AALA Accredited Laboratory. Mass standards are used quarterly to verify the scales are within required calibration tolerance. The mass standards have been evaluated by three different Accredited Laboratories. All electrical measuring equipment is calibrated by AALA Accredited Laboratories – two or more different laboratories depending upon the equipment. Coriolis meters and turbine meters from different manufacturers and are calibrated in different laboratories accredited by NVLAP or ILAC. All equipment and flow meters are from or have been calibrated in the U.S.A. or Germany.

H. Uncertainty analysis and calculations

Using ISO 4185 or ISO 9368-1, expanded uncertainty of the in-house static weigh standard is calculated with k=2 with: E_s = 0.0172% (RSS of Type A) and E_r = 0.0708% (RSS of Type B).

$$U_e = k * \sqrt{E_s{}^2 + E_r{}^2}$$

Various sections of ISO 5168, ISO/TR 7066-1 were used to analyse and calculate flow rate uncertainties.

IV. Results & discussion

Automation saved time by 90%, decreased measurement uncertainty by 10% and made some flow rate evaluations practical. Flow system flaws in pump and flow range were found by using the coriolis meters.

Automation increased amount of measurements and types of measurements that can be collected by several fold because of: 1) computer and instrument communication, 2) method changes for in-situation transfer standards, 3) external evaluation of transfer standards.

Many measurements can be made simultaneously because instruments report measurements to a computer file instead of the operator reading instruments and writing observed values on paper. The evaluation of the recirculating flow stand can be accomplished continuously at a single flow point for any length of time such as 1 minute to 8 hours with data collected every second. The time to evaluate the entire flow range with the automated data collection with the coriolis meter transfer standard is the same as the time to evaluate a single flow point with Flow Dump Weigh Standard.

Prior to automated data collection with the coriolis meter, the Flow Dump Weigh Standard Method could evaluate only a single flow point and the recirculating system could collect between 1 and 5 readings only. The number of flow system readings were dependent upon the flow dump sample collection time as a function of the flow rate, system tank size (flow rate changes with fluid level into pump), vessel size to capture all of the flow dump sample (every drop counts), as well as other error sources. For different flow rates, the Flow Dump Weigh Standard Method on the recirculating system required different collection times, different size collection vessels and different range scales. For flow rates below 3.785 LPM, the flow dump sample collection times ranged from 1 to 10 minutes. For flow rates above 37.854 LPM, the flow dump sample collection times were less than 30 seconds and increased the measurement uncertainty. Much time was required to setup the recirculating system to measure a single flow rate for the flow dump. Several flow runs were required to adjust the diverter valve output flow to match recirculating flow.

Flow system flaws in pump and flow range were found by using the coriolis meters as transfer standards.

The coriolis meters are used as flow transfer standards for mass and volumetric flow rates because the coriolis meter measures mass flow rate and temperature and can compute density and volumetric flow rate. All measured and computed data from the coriolis meter is evaluated with associated measurement uncertainty in the recirculating system and outside of the recirculating system.

Coriolis meters evaluated on the constant level head weigh standard were within 0.0023% of reading and had a standard deviation of 0.0003. These results were achieved with an open/close valve design, not the traditional diverter valve design.

There was less than 0.15% difference between densities reported by the coriolis meters, measured by the 100ml cup/scale and the densities calculated by three Internet water-density calculation websites. The density reported by the turbine meter flow stand was 19.87% higher than the coriolis meters.

There was less than 0.28% difference between temperatures measured by coriolis meter and a temperature reference with 0.012% expanded uncertainty. The temperature variations between the recirculating flow standard temperature probe at the flow-sensor-under-test location and the coriolis meter were within the manufacturer stated uncertainties.

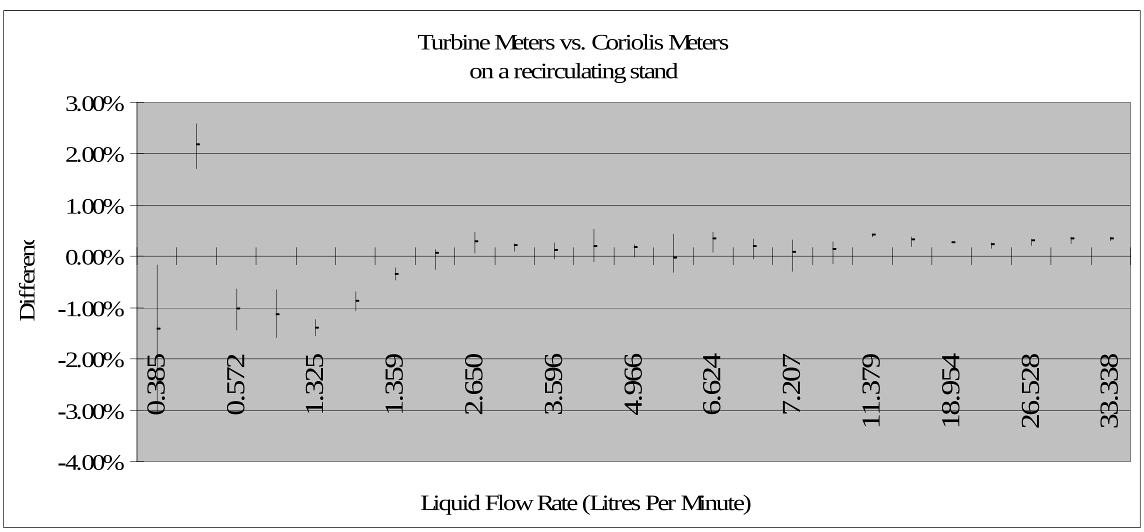

Figure 4. Differences between Turbine Meters and Coriolis Meters on Recirculating Flow System

Root cause analysis based upon data shown on Figure 4 revealed three findings:
1) The flow stand pump was not adequate to cover the entire flow range: flow rates below 11.379 LPM were not stable.
2) The lowest flow rate turbine meter had operating bias or was beyond range for flow rates below 1.359 LPM. A review of the Roshko-Strouhal graph for the lowest flow rate turbine meter showed flow rates below 1.359 LPM were in an undesirable portion of the curve - large slope change.
3) The turbine meters were more sensitive to the flow instability than the coriolis meters.

Electro-magnetic Interference (EMI) effects were discovered on the off-the-shelf recirculating flow systems. Usually the EMI effects caused ridiculously high or out-of-range readings. On a few occasions, the EMI effects caused readings to shift by 15% to 18%. Corrections were cable movement and cable shielding.

The off-the-shelf automated Roshko-Strouhal compensated turbine meter reference standard did not meet 0.25% of reading requirement/claim. Uncertainty analysis revealed expanded uncertainty was 1.27% because of temperature probe selection, viscosity calculation and over-extended flow ranges of turbine meter references. Manufacturer improved the off-the-shelf system offered to public.

V. Conclusions

It is possible to detect errors using less-than-state-of-the-art equipment. Automated data collection is required to collect simultaneous measurement data, guide calibration equipment operators to perform certain tasks, eliminate errors, make some measurements practical and reduce the cost of the measurements.

A benefit of coriolis meters as a flow rate transfer standard is capability to have a mass flow rate measurement and a volumetric flow rate calculation based upon a good quality temperature probe. For best uncertainty when used as a volumetric flow rate transfer standard, turbine meters should not exceed 7:1 turndown ratio for flow rate range.

Temperature probe uncertainty, cavitation, flow rate stability and EMI effects can have large impacts on flow rate calculations. Temperature and pressure probe placement is dependent upon design and must be located at flow-sensor-under-test and at various points along flow path to measure mass flow based upon thermal mass changes and storage. In recirculating systems, back pressure is required to keep the flow channel completely full – free of cavitation. Cavitation sources in the system are: trapped air in pipe connections, fluid re-entry relative to tank feed into pump, insufficient back pressure, and rotational objects heating fluid (pump, turbine sensor). Flow rate stability is a function of several things including tank size and shape, the entry point of returning fluid into feed tank as well as properly specified pumps. EMI effects can cause very large or small reading shifts and be latent design defects. Meter uncertainty claims by manufacturers are becoming more realistic. Establishing traceability to NMIs requires knowing the correct questions to ask of the correct individuals. Accredited laboratory calibrations between countries are traceable and within stated uncertainties.

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