Cryogenic Flow Facility at NIST

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A unique flow calibration facility for cryogenics liquid is located at the National Institute of Standards and Technology (NIST) in Boulder, Colorado. A dynamic weighing system is used to measure totalized mass flow and, with the use of NIST thermodynamic property data for density, volumetric flow. Calibrations are typically performed with liquid nitrogen in a flow range of 0.95 to 9.5 kg/s, pressure range of 0.4 to 0.76 MPa, and temperature range of 80 to 90 K.

History

In the late 1960's several events led the Cryogenics Division of the National Bureau of Standards to coordinate and develop a program on cryogenic flow metering. In 1967, the Compressed Gas Association (CGA) proposed a model code for flow metering of cryogenic fluids to the National Conference on Weights and Measures. This CGA proposal brought national attention to the problems associated with cryogenic flow measurement.

In 1968, the State of California adopted as law a code for cryogenic fluid measurement devices used in California.[1] This code was very similar to recommendations made in NBS Handbook 44.[2] The Cryogenics Division participated in the hearings and provided technical information and standard data for hydrogen, oxygen, argon, and nitrogen for incorporation into the code.

An Instrument Society of America ad-hoc committee provided an extensive review and definition of the broad national needs for cryogenic measurements and standards to ISC Conference in 1967.[3]

The Cryogenic Division, involved in all three of these events, responded with suggestions for a flow facility research facility and program to evaluate traditional metering methods, provide necessary methodology to preserve the accuracy and precision of field measuring methods, and to investigate new measuring methods. A joint coordination committee of NBS and CGA convened to tackle the problems of constructing a facility to measure moderate flows and develop a program that would have maximum impact in solving the requirements. The resulting facility, whose construction was sponsored by CGA, continues to operate today in much the same fashion as it did then; however, it is now under the direction of the Process Measurement Division of the National Institute of Standards and Technology (NIST).

In the late 1970's, the system was modified to conduct metering research using high-pressure gas at ambient temperature. This closed loop system still used the liquid nitrogen dynamic weighing system to measure mass flow rate. Throughout the 1980's, the Gas Research Institute (GRI) sponsored considerable orifice meter research with nitrogen gas in the modified flow loop, but liquid nitrogen meter calibrations continued to be performed.

The main focus of the flow facility has now returned to measurement of liquid nitrogen flow. As liquefied natural gas (LNG) becomes a viable alternative fuel, an expanding role for the flow facility is expected; however, calibrations and testing will continue to be done with liquefied nitrogen only.

Capabilities

The flow loop is a pumped continues system. This method of operation allows for: (1) thermal equilibrium to be obtained and (2) continuous operation without liquid loss. The facility design permits the establishment of system temperature, pressure, and the flow rate with the capability to maintain steady conditions for substantial time periods. Typical calibrations are:

Flowrate: 0.95 to 9.5 kg/s (2 to 20 lb/s, 20 to 200 gpm)
Pressure: 0.4 to 0.76 MPa (60 to 110 psia)
Temperature: 80 to 90 K (114 to 162^{o}R)

These flow parameters approximate the metering of commercial cryogenic fluids that might be encountered on truck-trailer type deliveries and provide a nearly full-scale test of a 50 mm (2 inch) flowmeter. A modification to the original system is being planned to improve the measurement below 0.95 kg/s and to better control conditions upstream of the meter being tested.

Components and Instrumentation

Figure 1 is a schematic of the liquid flow facility. Liquid nitrogen, the usual process fluid, is circulated throughout the closed loop by a variable-speed centrifugal pump. The liquid flows through the subcooler, a heat exchanger consisting of a finned tube submerged in a nitrogen bath where the thermal energy due to pumping and ambient heat leak is removed. The temperature of the liquid nitrogen in the flow loop can be changed or controlled by adjusting the liquid level and the vapor pressure in the subcooooler tank. Some of the test fluid also can be diverted around the subcooler, if necessary.

After leaving the subcooler and bypass, the fluid passes through a vacuum-jacketed loop containing an in-line heater, through the test section, and into the weigh tank/catch tank system (described below) which represents the heart of the measurement system. The liquid flows into the bottom of the weigh tank through a pipe and diffuser. The diffuser removes the vertical component of the flow. The liquid then flows through the weigh tank valve and into the catch tank, and is drawn back into the circulation pump.

The flow system is pressurized with helium gas to prevent the liquid nitrogen from boiling. The nitrogen is always subcooled by 10 to 15 K. Helium absorbed in the liquid nitrogen is not expected to exceed 0.5 mole percent, according to data by DeVaney, Dalton, and Meeks.[4] No test points are taken if evidence of bubbles is detected visually through a sapphire window located near the meter being tested.

The weigh tank, with a capacity of 0.378 cubic meters (100 gal) and a tare weight of approximately 70 kg (145 lb), is suspended from the load cell apparatus located in the dome above the catch tank. A mechanism in the load cell apparatus allows the sequential suspension of four weights from the load cell. Each weighs approximately 113 kg (250 lb), and they are used to establish the sensitivity of the load cell. The load cell sensitivity is determined before installation, and using the calibration weights, the load cell sensitivity is evaluated every day that the system is operated to ensure its operation has not shifted.

Periodically, these *in situ* data and recorded pressure information are used to update the load cell sensitivity equation. The catch tank is a stainless steel pressure vessel with a 0.443 cubic meters (117 gal) usable capacity. Both the weigh tank and the catch tank are contained in a vacuum-jacketed chamber.

The flow loop is particularly well-instrumented in the test section and the weigh tank/ catch tank assembly. This provides information needed to determine mass flow rate as well as fluid property information used to determine volume flow rate and weigh tank buoyancy effects.

Operation and Control

When the temperature and pressure in the system have reached steady state, a test point is taken. A test point is one mass measurement by the weigh tank and may include any or all of the following measurements; elapsed time, flowmeter output, temperatures, and pressures. To begin a test point, the weigh tank valve is closed and liquid nitrogen accumulates in the tank. The output voltage from the load cell is monitored by a voltage comparator, and as it reaches a preset level, data acquisition begins. A timer is initiated and a computer stores digitized information about the system and any flow measurement devices installed. For example, if a flow meter with a frequency output is installed in the test section, a counter counts the meter pulses while the computer records digitized outputs from pressure transducers, thermometers, and initial load cell signals.

As the weigh tank fills, the output voltage from the load cell is monitored. As it reaches a preset level, the test point ends, the weigh tank valve opens, and complete circulation resumes. Data acquisition stops and information from the timer, counters, and load cell voltmeter is sent to the main minicomputer. The load cell output is recorded at the beginning and at the end of the test point, and the difference in voltage is a measure of the accumulated mass. The mass accumulated for each data point is varied, but the average is approximately 181 kg (400 lb).

The flow rate through the test section is controlled by the combination of a control valve downstream from the test section and the circulation pump. Gross variations in pressure are controlled by addition of helium gas, with finer adjustments made by a combination of the flow control valve and pump. Temperature is controlled by the depth and vapor pressure of the subcooler bath, in-line heaters, and bypass flow.

The measurement of accumulated mass in the weigh tank and elapsed time allow computation of the mass flow rate during a test point; however, many of the meters tested measure volume flow rates. The pressure and temperature of the fluid is measured in close proximity to the flowmeters being tested. Using the recent equation of state formulation of Span[5] and coworkers presented in REFPROP,[6] the NIST thermophysical property software, the density is calculated and the volume rate through the meter can be derived. The REFPROP program replaces the older formulation of Younglove[7] that was distributed as part of the MIPROPs[8] computer program.

In the early days of cryogenic meter evaluation at this facility, a fractional factorial test plan was created to evaluate meter rangeability. This test plan is still used today. It allows evaluation of the meter for sensitivity to pressure, temperature, flowrate, and thermal cycling. Fifty-nine data points are taken over two days at five temperatures, 12 flow rates, and five pressures. If the meter measures volumetric flow rate, the predicted performance of the meter in measuring flow rate is compared to the flow rate determined in our facility by the equations:

$$\text{Meter Mass:} \qquad M_R = N*\rho/K \qquad (1)$$

$$\text{Percent Deviation} = (M_R - M_{NIST}) \times 100/M_{NIST} \qquad (2)$$

where, M_R = mass calculated from the turbine flowmeter output,
N = turbine flowmeter output (pulses),
ρ = liquid density calculated from the flow facility temperature and pressure measurements using equation of state from REFPROP,
K = uncompensated meter factor, and
M_{NIST} = mass measured from flow facility.

If the meter measures mass directly, the deviation is calculated using equation (2) only. The deviation data from equation (2) are fitted by the least-squares method the mathematical model in equation (3);

$$\text{Dev. (\%)} = A + B*Q + C*Q^2 + D*Q^3 + E*T + F*P, \qquad (3)$$

where, Dev. (%) = percent deviation,
T = fluid temperature (°R),
Q = volume flow rate (gallons per minute),
P = liquid nitrogen pressure (psia), and
A, B, C, D, E, and F = coefficients.

If the meter measures mass flow rate, the volume flow rate variable in equation (3) is replaced with a mass flow rate variable.

In general, flowmeters are much more sensitive to flow rate variations than pressure or temperature variations. Figure 2 illustrates the results of a typical flowmeter calibration; data were taken during a calibration of a 50 mm (2 in) turbine flowmeter.

Flow Measurement Uncertainty

The guidelines in NIST Technical Note 1297[9] are used to classify the types of uncertainties and determine their values.[10] The components of uncertainty are determined by statistical analysis of observed data, called Type A, from those determined by *a priori* information (for example, manufacturers uncertainties for electronic equipment), Type B. Most Type B uncertainties are those associated with instrumentation and thermophysical properties of the working fluid (liquid nitrogen) where the number of degrees of freedom is considered infinite. The uncertainty (2σ) of REFPROP for liquid nitrogen is 0.02 %.

The combination of all the uncertainties, in quadrature, is multiplied by a coverage factor of 2 in order to estimate an approximate 95 percent confidence interval for total system uncertainty. All sample sizes were large enough that a coverage factor of 2 was sufficient to estimate a 95 percent confidence interval.[9] Table 1 lists the overall uncertainty associated with cryogenic flow measurement at NIST.

Table 1. Flow measurement uncertainty evaluated at 181.4 kg and 100 seconds

Weigh Tank System	Using REFPROP	Without REFPROP
LN2 mass flow	0.170	0.170
LN2 volume flow	0.180	0.178

Conclusion

Throughout many years of operation, the facility has been well used in evaluating various types of flowmetering devices to determine their application in measuring cryogenic flows. Types of flowmeters examined include: positive displacement, turbine, head-type (orifice), angular momentum, Coriolis force, and vortex shedding flowmeters. For many years NIST has calibrated the transfer standard meter for the Department of Agriculture of the State of California. It is expected that LNG will have an expanding role as an alternative fuel and NIST will be able to provide assistance in developing accurate measurement methods for LNG flows. NIST is committed to maintaining the quality of this facility and to continuing to provide this unique flow measurement capability to its customers.

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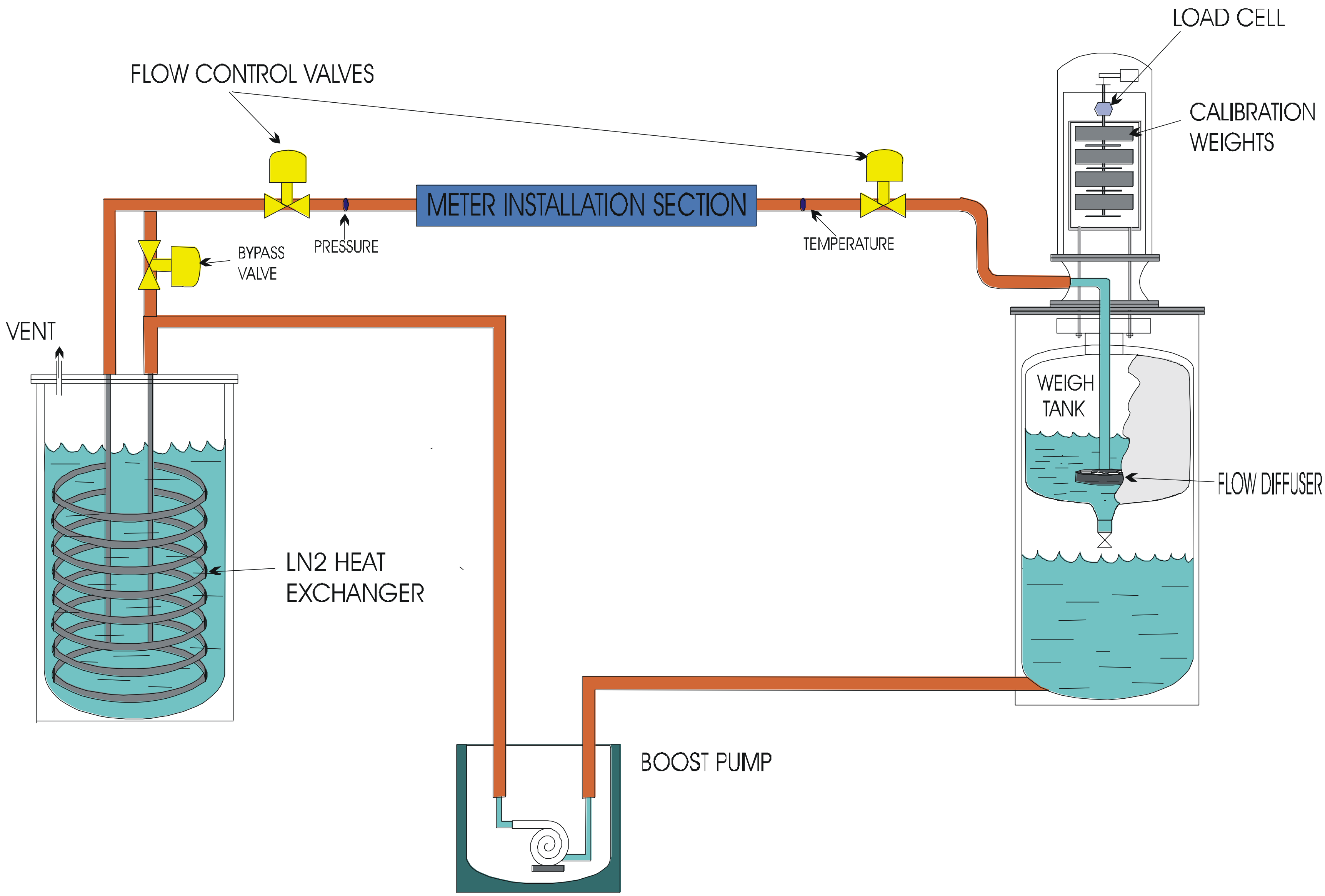

Figure 1. Schematic of the Liquid Nitrogen Flow Calibration Facility.