flotek.g 2017-“Innovative Solutions in Flow Measurement and Control -Oil, Water and Gas” August 28-30, 2017, FCRI, Palakkad, Kerala, India

Conversion factors for Thermal Mass flow meters for different operating mediums: An Experimental study

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ABSTRACT

Thermal Mass flow meters use the thermal properties of the fluid to measure the flow of a fluid flowing in a pipe or duct. In a typical thermal mass flow meter, a measured amount of heat is applied to the heater of the sensor. Some of this heat is lost to the flowing fluid. As flow increases, more heat is lost. The amount of heat lost is sensed using temperature measurement(s) in the sensor. The transmitter uses the heat input and temperature measurements to determine fluid flow. Therefore, it is important for the thermal mass flow meter supplier to know the properties of the fluid so that the proper calibration factor can be used to determine the flow rate accurately for operating mediums different from actual calibration medium. Due to this constraint, thermal mass flow meters are commonly applied to measure the flow of pure gases. Suppliers can provide appropriate calibration information for other gases, however the accuracy of the thermal mass flow meter is dependent on the actual gas being the same as the gas used for calibration purpose. In other words, the accuracy of a thermal flow meter calibrated for a given gas will be degraded if the actual flowing gas is different from the Calibrated gas. Theoretical conversion from one gas to another is very difficult and can result in large errors, especially if using the manufacturer's conversion factors.

A series of flow performance tests were carried out on a 22 lpm Thermal Mass flow meter of inlet size less than 1inch with different mediums. Gases used for the studies are Air, Nitrogen, Argon, Helium and Carbon dioxide. The correction factors in Thermal mass flow meter for its application in different mediums estimated using experimental methods were compared with specified factors for different mediums recommended by the manufacturer of the flow meter. A Primary proving system was used for measurement of actual flow in the test run.

Keywords: Thermal Mass flow meters, Gas Correction factor, Calibration

1. ABOUT FCRI

The Fluid control Research Institute (FCRI) an autonomous R&D Institute was established in 1987 with active assistance and participation from UNDP and UNIDO, under the Ministry of Industry (Govt. of

India). The Institute is accredited by different National/International bodies such as National Accreditation Board for Testing and Calibration Laboratories (NABL, India); Underwriters Laboratory, USA; Chief Controller of Explosives, Nagpur-India; Bureau of Indian Standards (BIS); NMI, Netherlands; Department of weights and measures, India; Central Pollution Control Board(CPCB, India); Department of Science and Technology, India; etc. FCRI regularly participates in International round robin proficiency test programs in association with NIST, USA; CEESI, USA; NEL, UK; DELFT, Holland; DTI, Denmark; and KRISS, Korea etc. Other than flow laboratories with Air, Water and Oil as media, FCRI has got supporting laboratories like metrology section, Noise and Vibration section, and Electronics and Instrumentation section etc. FCRI regularly conducts National/International level Conferences/Training programs. FCRI also develops software in the field of flow meter design and selection valves/pumps, natural gas metering etc.

2. PRIMARY CALIBRATION FACILITIES AT FCRI

Primary Air flow Calibration facility at FCRI is equipped with internationally accepted primary flow standards like Bell Provers and Piston Provers of various capacities for precise flow measurement. Calibration of flow meters at low pressure is carried out here for flow ranges up to 40 m^3/h. As per the norms stipulated by the ISO, Primary air flow lab is always maintained at controlled ambient conditions (20±0.5^{0}C, 55±5 % RH) for ensuring metrological qualities of the master flow meters and thereby providing highest quality and precision in calibration of flow meters.

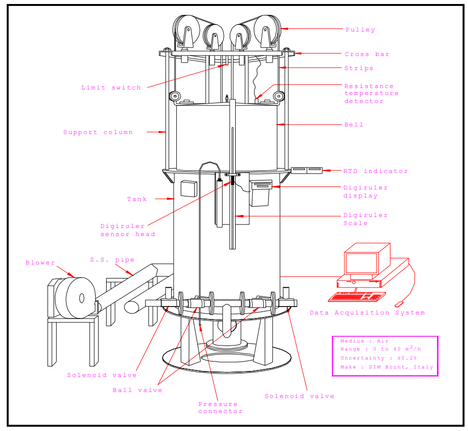

Fig 1. Schematic of 500ltr Bell Prover at Air Flow Laboratory

3. DESCRIPTION OF 50 LTR BELL PROVER SYSTEM

A primary standard Bell prover calibration system is used to accurately measure a displaced volume of gas at a constant pressure. Interface electronics are provided to measure displaced volume and the time over which the volume is displaced so that a precise flow rate can be determined. To calibrate a flow meter using the Bell prover, the flow meter must be installed upstream of the bell so that all gas flowing through it is captured by the calibrator. The System consists of a vertical inner tank surrounded by an outer shell. The annular space between the inner tank and outer shell is filled with sealing liquid (Oil). An inverted tank, called the bell, is placed over the inner tank with the wall of the bell riding in the annular space filled with sealing liquid. The liquid provides a bubble-tight, friction-less seal which allows for smooth linear movement of the bell at essentially zero pressure drop.The bell is precision-balanced so that pressure remains constant throughout the stroke. A large counterweight is used to balance the weight of the bell while a small counterweight hanging from an involute cam is used to compensate for buoyancy and other linear effects experienced by the bell as it moves along its stroke.The Bell prover has a feature that a large counterweight is suspended in small tank which is hydraulically connected to the annular space in which the bell rides. The counterweight is machined so that its cross-sectional area exactly matches the cross-sectional area of the bell. As the bell moves out of the sealing liquid, the counterweight moves into the liquid so that the level of the sealing liquid remains constant. This allows for a more accurate/repeatable calibration since the varying liquid level is no longer an influence. The bell is a precision cylinder so that linear movement of the bell is proportional to displaced volume. A rotary encoder is directly coupled to the pulley shaft and produces pulses proportional to the linear displacement of the bell. Interface electronics provide a means of counting the encoder pulses. An exact number of pulses and corresponding time are accumulated over a calibration run.

The following are the salient features of the facility.

Method	: Bell Prover
Primary parameter	: Volume
Medium	: Compressed Air/Nitrogen/
Temperature	: 20 ± 0.5 °C.
Flow rate	: 0.03 to 16m3/h
Uncertainty	: ± 0.3%

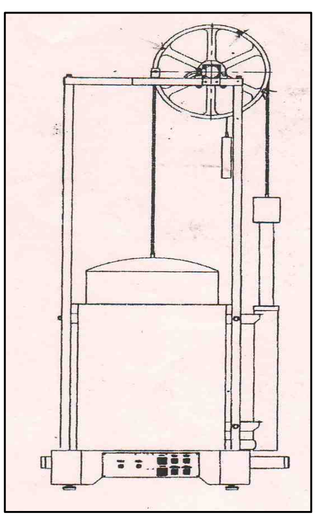

Fig 2- 50ltr Bell prover system at FCRI

4. THERMAL MASS FLOW METER OPERATING PRINCIPLES

4.1 Capillary Thermal Mass flow meter (CTMF meter)

A typical CTMF meter consists of a meter body and flow sensor. The flow sensor is mounted into the meter body. A defined portion of the gas flow from the meter body is diverted through the (By pass) flow sensor, through which the gas flow rate is measured.

Fig 3 shows a simplified CTMF meter with a flow sensor consisting of a thin tube and two temperature sensors. Depending upon the meter manufacturer the heater can either be combined with each temperature sensor or be located separately in the middle of the flow sensor ie between the temperature sensor upstream (T1) and the one downstream (T2) of the gas flow. A precision power supply delivers constant heat to the flow sensor. Under stopped flow conditions, both sensors measure the same temperature. As the flow rate increases, heat is carried away from the upstream sensor (T1) towards the downstream (T2). A bridge circuitry interprets the temperature difference and an amplifier provides the flow rate output signal. The measured temperature difference between the two sensors is proportional to the mass flow rate.

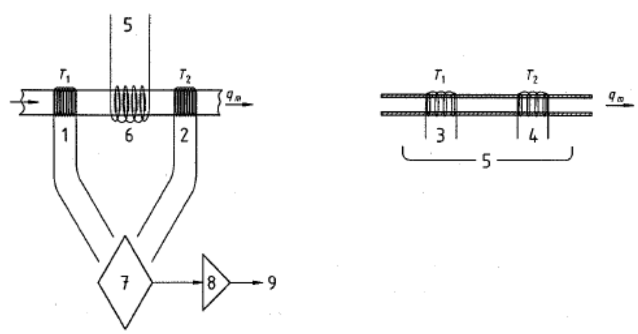

Fig 3 -Simplified CTMF meter

Where

1. Upstream temperature sensor (T1)
2. Downstream temperature sensor (T2)
3. Upstream temperature sensor (T1) with heater
4. Downstream temperature sensor (T2) with heater
5. Constant power supply P
6. Heater
7. Bridge circuitry
8. Amplifier
9. Flow signal output (0V to 5V dc or 4 mA to 20mA)

The flow sensor measures the mass flow rate as a function of temperature difference. This can be expressed according to first law of thermodynamics (heat in= heat out, for no losses) for which the following equations apply.

$$P=q_m \times C_p \times (T_2-T_1)$$

Where

q_m is the mass flow rate, expressed in kg/s

Cp is the specific heat, expressed in joules per kilogram per Kelvin of the gas at constant pressure

T_2-T_1 is the temperature difference, expressed in Kelvin

P is the constant input power, expressed in watts

5. CALIBRATION OF THERMAL MASS FLOW METER USING BELL PROVER WITH DIFFERENT MEDIUMS

A 22 slpm Thermal mass flow meter was used for the study and a series of flow performance tests were conducted with different mediums. Gases used for the studies are Air, Nitrogen, Argon, Helium and Carbon dioxide. A Primary proving system (Bell Prover) was used for the measurement of actual flow in the test run. The Thermal Mass flow meter was mounted at the upstream of the reference Bell Prover. After ensuring the leak tightness, the calibration was done for specified flow rates covering the entire range of the Thermal Mass flow meter. The required flow rate was maintained using a Mass flow controller and it was allowed to pass through the Thermal mass flow meter and then to the reference Bell prover. Bell prover is provided with an optical encoder, generating a pulse representing an incremental change in the displaced volume. Provision was made for the measurement of pressure and temperature at reference Bell Prover location. The reference flow rate was measured from the data obtained from the Bell prover and it was compared with the flow rate indicated by the Thermal mass flow meter. The Calibration was repeated using different gases. The specification of the Thermal Mass flow meter was given below.

Type: Thermal Mass Flow Meter
Range: 0-22Slpm (For Air medium)

6. CONVERSION FACTORS FOR VARIOUS MEDIUMS (THEORETICAL PUBLISHED DATA)

All the Calibrations cannot be performed using the desired process gas due to various reasons. It this cases it is a common practice to use a reference gas like air or nitrogen for calibration. Gas conversion factors K have been used since the first commercialization of capillary tube thermal MFMs and MFCs to convert the flow calibration for a reference gas to any other gas. Most manufacturers provide a list of gas conversion factors relative to a single primary reference gas, usually air or nitrogen.

The Conversion factor K is defined as

$$K = \frac{\mathrm{Cp.ref} \times \mathrm{\rho n.ref}}{\mathrm{Cp.proc} \times \mathrm{\rho n.proc}}$$

Where

Cp.ref is the specific heat, at constant pressure, of the reference gas;

Cp.proc is the specific heat, at constant pressure, of the process gas;

ρn.ref is the density at normal conditions, of the reference gas

ρn.proc is the density at normal conditions, of the process gas

The below table shows the K-factor of commonly used gases provided by the manufacturer for conversion from one gas to another.

Name of the gas	Symbol	Density ρ_n (kg/m3) 0°C, 1 atm	Heat capacity Cp-ca l[cal/g.k] 20°C, 1 atm	Thermal conductivity,k (W/m.K) 20°C	Conversion factor,K 20°C, 1 atm
Air	Air	1.293	0.241	0.025596	1
Nitrogen	N_2	1.25	0.249	0.025468	1
Argon	Ar	1.784	0.125	0.017391	1.4
Helium	He	0.1785	1.24	0.14786	1.41
Carbon dioxide	CO_2	1.977	0.213	0.016225	0.74

Table 1- Gas properties and Conversion factor for different gases

7. CONVERSION OF FLOW FROM ONE GAS TO ANOTHER (EXPERIMENTAL METHOD)

The conversion factors in Thermal mass flow meter for its application in different mediums were estimated using the experimental methods relative to air medium.

Estimated Conversion factor K,

$$Kest = \frac{\mathrm{Qref.}}{\mathrm{Qind.}}$$

Where

Q_{ref} is the reference flow rate from the Bell Prover for a particular gas.

Q_{ind} is the flow rate indicated by the Thermal Mass flow meter for air medium.

8. RESULTS

Indicated flow rate, flow rate after applying manufacturer specified conversion factor, actual flow rate, estimated conversion factor and error in flow rate after applying manufacturer conversion factor are given in Tables 2 to 8 for different gases.

Sl. No.	Meter under Calibration: Indicated flow, q_i (slpm)	Actual flow rate q_a (slpm)	Error $(q_i-q_a)/q_a*100$ (% rdg)
1	2	3	4
1	22.06	22.05	0.06
2	17.57	17.55	0.12
3	15.18	15.19	-0.06
4	12.55	12.55	-0.02
5	10.00	10.01	-0.05
6	7.45	7.44	0.08
7	5.18	5.18	0.10
8	3.17	3.17	-0.13

Table 2- Results of Calibration of Thermal Mass flow meter using Air medium

Sl. No.	Meter under Calibration		Actual flow rate q_a (slpm)	Estimated Conversion factor K_{est} (q_a/q_i) -	Error after using manufactuer conversion factor $(q_t-q_a)/q_a*100$ (% rdg)
	Indicated flow rate (air medium) q_i (slpm)	Flow rate after applying manufacturer conversion factor, q_t (slpm)			
1	2	3	4	5	6
1	21.99	21.99	22.05	1.0026	-0.26
2	17.49	17.49	17.54	1.0029	-0.29
3	15.27	15.27	15.32	1.0031	-0.31
4	12.44	12.44	12.48	1.0035	-0.34
5	10.20	10.20	10.24	1.0043	-0.43
6	7.40	7.40	7.43	1.0041	-0.40
7	5.10	5.10	5.12	1.0039	-0.39
8	3.15	3.15	3.18	1.0108	-1.07

Table 3- Results of Calibration of Thermal Mass flow meter using Nitrogen medium

Sl. No.	Meter under Calibration: Indicated flow rate (air medium) q_i (slpm)	Meter under Calibration: Flow rate after applying manufacturer conversion factor, q_t (slpm)	Actual flow rate q_a (slpm)	Estimated Conversion factor K_{est} (q_a/q_i) -	Error after using manufactuer conversion factor $(q_t-q_a)/q_a*100$ (% rdg)
1	2	3	4	5	6
1	15.96	22.34	23.72	1.4859	-5.78
2	14.19	19.87	20.91	1.4733	-4.97
3	12.36	17.30	18.05	1.4603	-4.13
4	10.88	15.23	15.78	1.4499	-3.44
5	8.98	12.57	12.93	1.4397	-2.76
6	7.57	10.60	10.86	1.4351	-2.45
7	5.92	8.29	8.46	1.4290	-2.03
8	4.55	6.37	6.49	1.4274	-1.92
9	3.45	4.83	4.92	1.4252	-1.77

Table 4- Results of Calibration of Thermal Mass flow meter using Argon medium

Sl. No.	Meter under Calibration: Indicated flow rate (air medium) q_i (slpm)	Meter under Calibration: Flow rate after applying manufacturer conversion factor, q_t (slpm)	Actual flow rate q_a (slpm)	Estimated Conversion factor K_{est} (q_a/q_i) -	Error after using manufactuer conversion factor $(q_t-q_a)/q_a*100$ (% rdg)
1	2	3	4	5	6
1	15.79	22.26	21.26	1.3462	4.74
2	15.61	22.01	21.10	1.3515	4.33
3	12.50	17.63	17.12	1.3692	2.98
4	10.70	15.09	14.80	1.3832	1.94
5	8.57	12.08	11.97	1.3970	0.93
6	6.51	9.18	9.18	1.4094	0.04
7	4.49	6.33	6.39	1.4241	-0.99
8	3.09	4.36	4.43	1.4340	-1.67

Table 5 - Results of Calibration of Thermal Mass flow meter using Helium medium

Sl. No.	Meter under Calibration: Indicated flow rate (air medium) q_i (slpm)	Meter under Calibration: Flow rate after applying manufacturer conversion factor, q_t (slpm)	Actual flow rate q_a (slpm)	Estimated Conversion factor K_{est} (q_a/q_i) -	Error after using manufactuer conversion factor $(q_t-q_a)/q_a*100$ (% rdg)
1	2	3	4	5	6
1	23.37	17.29	19.43	0.8312	-10.97
2	22.03	16.30	18.09	0.8213	-9.90
3	17.89	13.24	14.26	0.7968	-7.13
4	14.13	10.46	11.02	0.7798	-5.11
5	12.20	9.03	9.44	0.7738	-4.36
6	10.11	7.48	7.77	0.7681	-3.65
7	7.35	5.44	5.60	0.7623	-2.93
8	5.15	3.81	3.92	0.7610	-2.76

Table 6- Results of Calibration of Thermal Mass flow meter using CO_2 medium

Sl no.	Name of the gas	Symbol	Theoretical Conversion factor, K_t	Average Experimental Conversion factor, K_e	Deviation between Theoretical & Experimental K-factors
1	Air	Air	1	-	
2	Nitrogen	N2	1	1.0044	0.44%
3	Argon	Ar	1.4	1.4473	3.37%
4	Helium	He	1.41	1.3893	-1.47%
5	Carbon dioxide	CO2	0.74	0.7868	6.32%

Table 7- Theoretical and Experimental conversion factors

Sl no.	Name of the gas	Symbol	Heat capacity Cp-ca l[cal/g.k] 20°C, 1 atm	Thermal conductivity,k (W/m.K) 20°C	Deviation between Theoretical & Experimental K-factors
1	Air	Air	0.241	0.025596	-
4	Helium	He	1.24	0.14786	-1.47%
2	Nitrogen	N2	0.249	0.025468	0.44%
3	Argon	Ar	0.125	0.017391	3.37%
5	Carbon dioxide	CO_2	0.213	0.016225	6.32%

Table 8- Thermal Conductivity of gases and Deviation between Theoretical & Experimental conversion factors

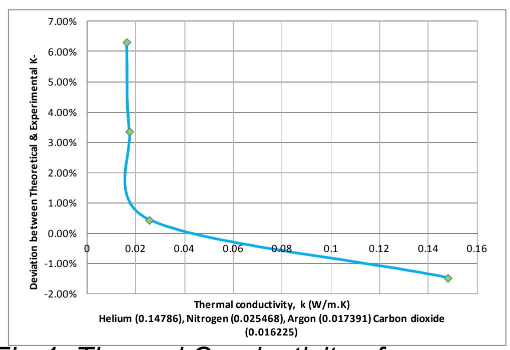

Fig 4- Thermal Conductivity of gases and Deviation between Theoretical & Experimental conversion factors

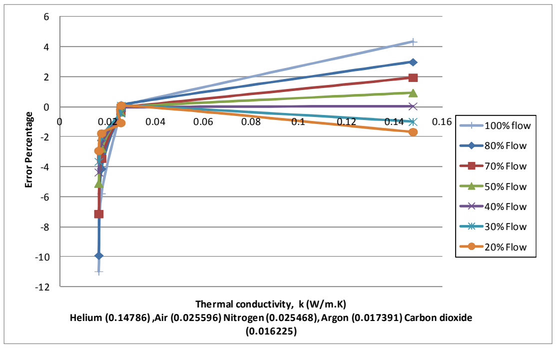

Fig 5- Thermal Conductivity of gases Vs Percentage Error for different flow rates

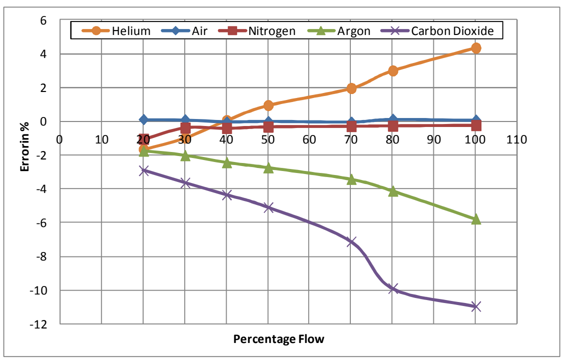

Fig 6- Percentage flow Vs Percentage error for different mediums

9. OBSERVATIONS BASED ON EXPERIMENTAL DATA

- Theoretical conversion for Thermal mass flow meters can usually be expected to be within 11% or better when using manufacturer's factors based on the experimental data for different mediums.
- Maximum deviation of 6.3% is observed in the average experimental Conversion factor from the theoretical conversion factor for the CO_2 medium from the air medium.
- Minimum deviation of 0.44% is observed in the average experimental Conversion factor from the theoretical conversion factor for the Nitrogen medium from the air medium and this may be due to the similar properties of air and Nitrogen.
- For higher thermal conductivity gases the error is observed in the positive side and vice versa in the case of low thermal conductivity gases.
- As the thermal conductivity of the fluid is higher which in turn results in higher heat transfer and hence the higher temperature difference between the sensors. Higher temperature difference causes more error on the positive side and vice versa.
- Helium is having the largest thermal conductivity(k=0.14786 W/m.K) in the Calibrated gases, which is having a higher positive error of approximately 5% and the Carbon dioxide is having the lowest thermal conductivity(k= 0.016225W/m.K) which resulted in a higher negative error in the order of approximately -11%.

10. CONCLUSION

- Thermal Mass flow meters are capable of good accuracy (1% or better) if they are calibrated on the actual process gas.
- Theoretical conversion from one gas to another is very difficult and can result in large errors, especially if using the manufacturer's conversion factors.
- The manufacturer conversion factor is derived based on the Specific heat and density of the reference and process gases. But the above experimental result shows that the error of the Thermal mass flow meter is also depending on the Thermal conductivity of gases which is not addressed.

REFERENCES

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