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Thermal Mass Flow Controller Induced Temperature Fluctuations in a Gas Flow Calibration Line at NMISA

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Abstract

The National Metrology Institute of South Africa's (NMISA) gas flow laboratory uses TMFCs to control gas flow rate during calibration of gas flow meters. The TMFC is connected upstream of the unit under test (UUT) during calibration. The laboratory performs gas flow calibrations in the range 5 mL/min – 50 L/min using nitrogen as flow medium. The gas temperature at the UUT's location downstream of an TMFC has been found to fluctuate proportionally to the change in the flow rate at flow rates above 250 mL/min and below 22.5 L/min. This temperature fluctuation has a significant effect on measurements by volumetric gas flow meters not installed with temperature and pressure sensors. The temperature fluctuations are attributed to heat generated by the MFC electronics and transferred via thermal convection currents, and the heat absorbed by the gas flowing through the capillary sensor tube.

This paper discusses gas temperature fluctuations observed at the NMISA flow laboratory as gas flow rate is changed using a TMFC. It also discusses a calibration setup used to measure temperature and pressure at the UUT's location for volumetric gas flow meters without temperature and pressure sensors. These temperature and pressure measurements allow the metrologist to convert volumetric flow rate to mass (standardised) flow rate at a specific temperature (T_s) for instruments such as bubble flow meters. The temperature T_s is chosen such that it matches field temperature as close as possible.

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1. Introduction

Thermal mass flow controllers/meters (TMFCs/TMFMs) are used to precisely control and deliver stable gas flows in several industries such as pharmaceutical and semiconductor industries. Thermal mass flow meters have been used in the semiconductor industry for more than 45 years [1]. Thermal mass flow meters measure "mass" flow of a gas directly instead of volume flow. This is done by measuring heat transferred to a gas flowing through a small capillary tube. The capillary tube (sensor tube) is a long thin stainless-steel tube with a small diameter of 0.25 – 1 mm [1]. Its length can be 100 times greater than its diameter [2]. When an TMFM is installed with a control valve, such as a solenoid valve, it then becomes an TMFC. As TMFMs/TMFCs measure mass flow, their measurements are insusceptible to gas temperature and pressure fluctuations. On the other hand, volume flow meters require additional temperature and pressure sensors to account for temperature and pressure changes. In practice, gas flow is usually converted to "mass" flow at certain standard temperature and pressure and is referred to as standardised flow rate. Volume flow is related to mass flow using the equation [1]

$$Q_s = Q_v \frac{T_s P_a}{T_a P_s} \qquad (1)$$

where Q_s, Q_v, T_s, T_a, P_s and P_a are the standardised and volumetric flow rates, standard and actual temperatures, standard and actual pressures, respectively. Equation (1) allows for the conversion of volumetric flow rate Q_v to mass flow Q_s at certain standard temperature and pressure conditions (T_s and P_s).

2. Principles of thermal mass flow meters/controllers

Typically, a TMFM/C consist of a thin long stainless-steel capillary tube wrapped with heating and temperature sensing wires (T_1, T_2) as shown in Figure 1. The heater constantly heats the capillary tube such that at zero flow, the temperature at T_1 is equal to the temperature at T_2. When there is gas flow, the temperature profile is skewed with T_2 at a higher temperature than T_1. The temperature difference ($\Delta T = T_2 - T_1$) between T_2 and T_1 is said to be linearly dependent to mass flow (molar flow, *m* in mol/s) [1]

$$m = \frac{Q}{C_p(T)\Delta T} \qquad (2)$$

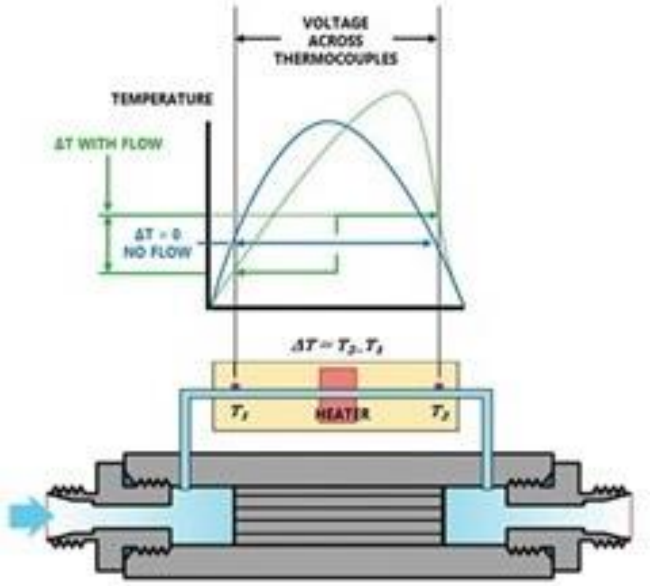

Figure 1 Shows basic design principle of a TMFM and temperature profile at zero and positive flow. Figure obtained from Ref. [3].

or [3]

$$\Delta T\left(\frac{\Delta m}{\Delta t}C_p(T)\right) = \alpha P_w \qquad (3)$$

where Q is the rate of heat transfer, $C_p(T)$ is the temperature dependent molar heat capacity ($Jmol^{-1}K^{-1}$), $\Delta m/\Delta t$ is the mass flow rate, α is a proportionality constant and P_w is heater power setting. In principle, this metering method utilizes the ability of a gas to absorb and transfer heat from one point to another.

To complete an TMFC, an electrically controlled valve such as a solenoid valve is installed in an TMFM. A solenoid valve is equipped with a plunger forced against an orifice by a mechanical spring. The flow is then controlled by an electrically energized solenoid coil which uses magnetic force to push the plunger away from the orifice and thus allowing gas flow. The output of the metering part of the TMFC is used to continuously adjust the electrical input to the solenoid valve.

3. Calibration setup used at the NMISA gas flow laboratory

The NMISA Gas Flow laboratory uses TMFCs to regulate gas flow rate during calibration of gas flow meters. The TMFC is usually connected upstream of the unit under test (UUT) as shown schematically in Figure 2.

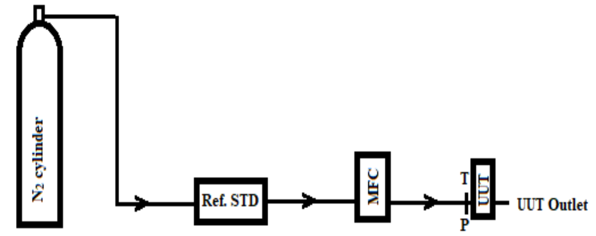

Figure 2 Schematic diagram of a calibration setup used at NMISA for volumetric gas flow meters.

When volumetric meters are calibrated, temperature and pressure sensors are connected at the location of the UUT to measure the actual gas temperature and pressure (see location of T and P in Figure 2). The temperature and pressure measurements are then used with Equation 1 to convert the UUT's volumetric flow rate to mass flow rate at certain standard temperature and pressure conditions. The standard conditions are chosen to closely match the conditions at which the UUT will be used by the client. Measuring the temperature at the UUT reduces errors that may arise due to gas expansion with gas temperature changes.

4. Results and discussion

Gas temperature was measured as a function of gas flow rate in the range 25 mL/min – 30 L/min using the calibration setup shown in Figure 2. Several TMFC models were used with at least 60 minutes of warm up time. These TMFC models have flow ranges 500 mL/min (MFC1A & MFC1B), 5 000 mL/min (MFC2A & MFC2B) and 50 L/min (MFC3A). In the range 25 – 250 mL/min, the average temperature change did not show any conclusive trend of increase or decrease as can be seen in Figure 3 (a) – (c). The temperature changes in this flow range were found to be within 0.11 °C comparing the temperature at the lower and upper end of the flow range. Figure 4 shows the gas temperature as a function of flow rate in the range 500 – 5 000 mL/min. In this range, the temperature was observed to increase as the flow rate was increased for both MFC2A and MFC2B. For each measurement session, measurements were taken from 10 – 95 % (T1-Up), 95 – 10 % (T1-Down), 10 – 95 % (T2-Up) and finally 95 – 10 % (T2-Down) of flow range. Figure 4 (a) and 4 (b) show that the gas temperature increased with increasing flow rate and decreased with decreasing flow rate during the calibration.

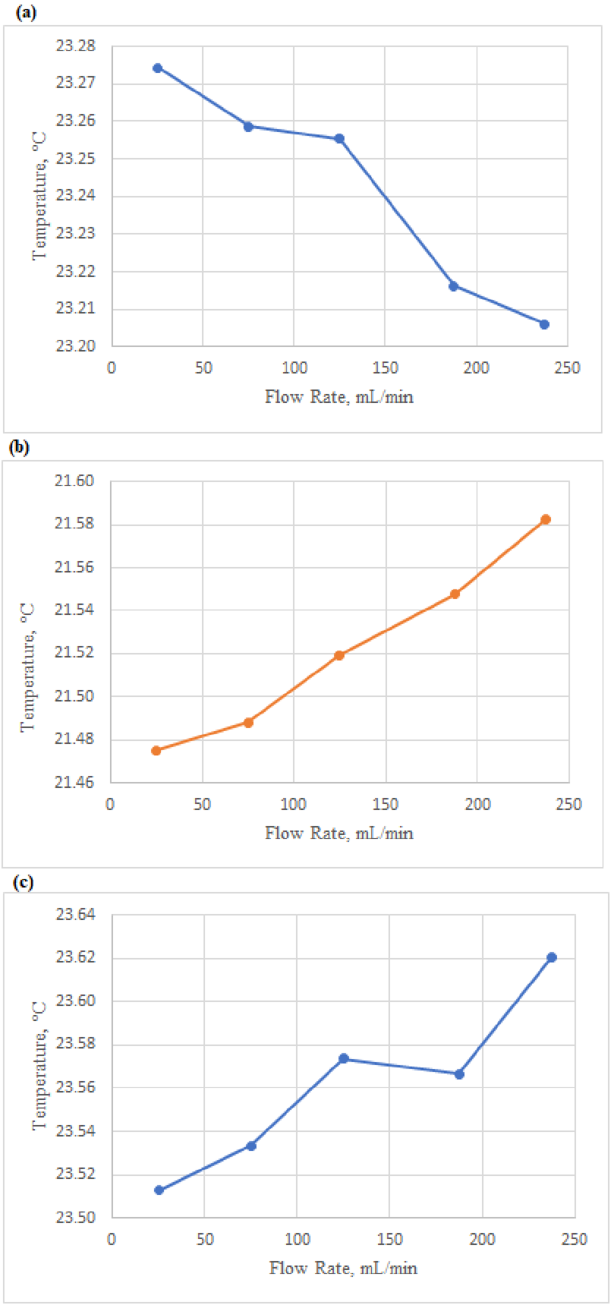

Figure 3 Shows the average gas temperature during calibration with MFC1B (a & b) and MFC1B (c).

Figure 5 (a) and 5 (b) show the average gas temperature clearly showing the change in gas temperature as the flow rate was changed for both MFC2A and MFC2B. MFC3A was used for calibrations above 5 000 mL/min. Similar to MFC2A and MFC2B, the gas temperature increased/decreased with increased/decreased flow rate in the range 2 – 10 L/min as shown in Figures 6 (a) and 6 (b). However, the gas temperature reached a plateau at flow rate ≥ 22.5 L/min as shown in Figures 7 (a) and 7 (b).

The TMFCs measure gas flow using transfer of heat into the gas using heating coils.

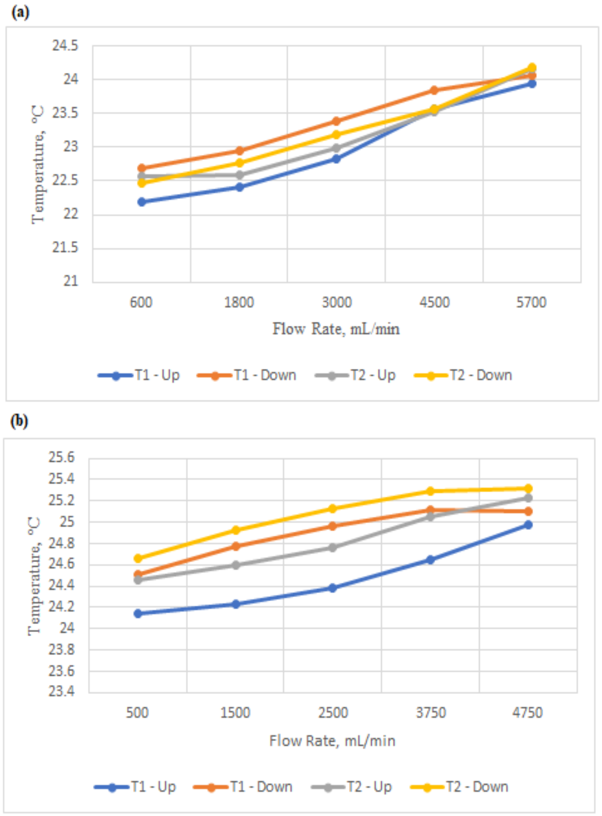

Figure 4 Shows gas temperature in the range 0.5 - 5 L/min for (a) MFC2A and (b) MFC2B.

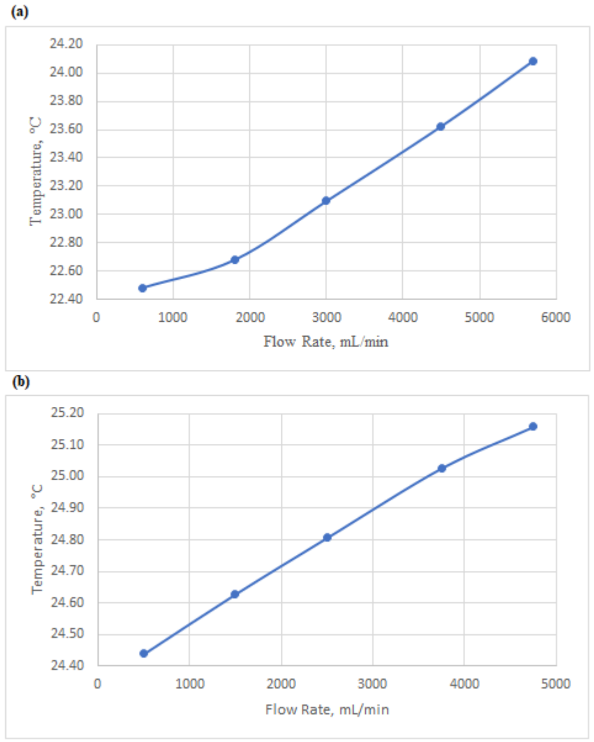

Figure 5 Shows the average gas temperature for the calibration sessions in Figure 4. MFC2A was used in (a) and MFC2B in (b)

The coils receive a constant heating current to heat the capillary tube to temperatures as high as 100 °C above ambient temperature [4]. This then suggests that the gas flowing through the capillary tube will be at an elevated temperature compared to the gas flowing through the main bypass tube. As a result, the final gas temperature may increase when these two gas streams mix. The electronics within the MFC casing generate heat and thermal convection currents that can transfer heat to the sensors thereby causing errors in the gas flow readings [3]. This heat can also be transferred to the gas flowing through the main bypass thereby contributing to its temperature increase.

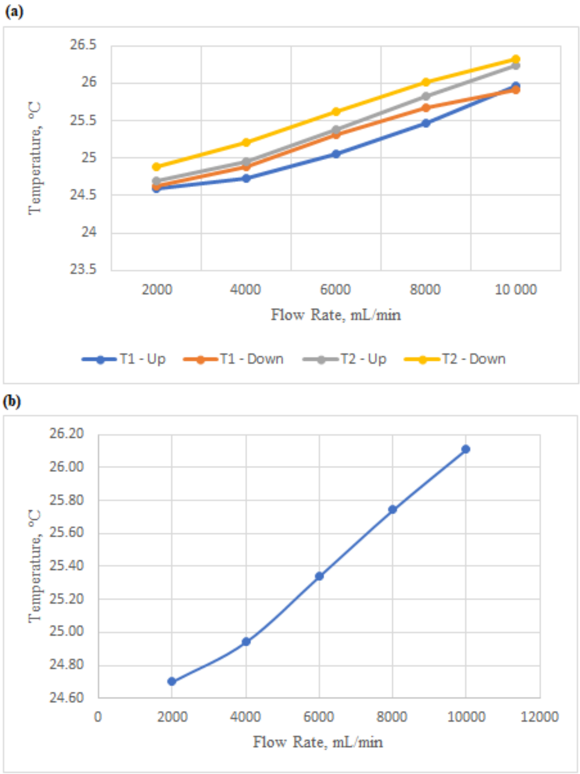

Figure 6 Shows (a) gas temperature and (b) average gas temperature in the range 2 - 10 L/min using MGC3A.

The mass flow signal from the TMFC sensor tube becomes non-linear at higher flows [2]. To linearize the signal at high flows, TMFCs that measure the heat (power) input required to hold ΔT constant were developed [2]. That is, as the flow increases, more heat (power) is added to increase the temperature of T_1. This then could explain the increase in temperature as the flow rate increases. However, as the flow increases, the heated fraction of gas becomes insufficient to increase the temperature of the gas flowing through the main bypass. Hence, at 22.5 L/min the gas temperature reaches a plateau, see Figure 7.

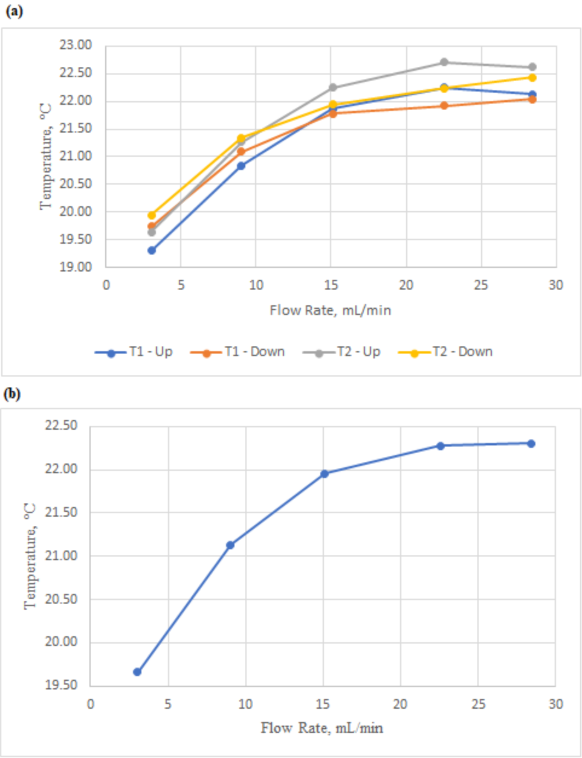

Figure 7 Shows (a) gas temperature and (b) average gas temperature in the range 3 - 28.5 L/min using MGC3A.

5. Conclusion

We have shown how gas temperature at UUT location changes with the change in the flow rate in the range 0.25 – 22.5 L/min in our facility. The gas temperature reaches a maximum at 22.5 L/min. The gas temperature change is attributed to the generated by the electronics of the TMFC and the heat absorbed by the gas flowing through the heated sensor tube. However, at high flow rates (>22.5 L/min), this heat combination is no longer sufficient to increase the temperature of the gas flow through the main bypass. To reduce measurement errors caused by the gas temperature fluctuations, our facility measures the gas temperature at the UUT's location and convert volumetric flow rate to mass flow rate.

References

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