Thermal mass flowmeters and pressure compensation: when is pressure compensation important?

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A frequently asked question by customers is: *"When is it necessary to use pressure compensation for a thermal mass flowmeter?"* If you have spent any time searching the internet for thermal flowmeter suppliers, what you may have noticed is that many of these promote the thermal mass flow measuring principle as a "pressure and temperature independent" principle. Most of the time there is no explanation as to why this is the case, but if you search long enough you may come across such an explanation as offered by Sage Metering, Inc.:

> *"A thermal mass flow meter is a precision instrument that measures gas mass flow. It represents an entirely different method for measuring flow rate [Entirely different from what? The Coriolis measuring principle is also entirely different from that for vortex meters and these entirely different from ultrasonic flowmeters]. These meters measure the heat transfer as the gas flows past a heated surface. The gas molecules create the heat transfer, the greater the number of gas molecules in contact with the heated surface the greater the heat transfer. Thus, this method of flow measurement is dependent only on the number of gas molecules and is independent of the gas pressure and gas temperature."* [1]

Of course, what this is saying is that because thermal **mass** flowmeters measure mass directly, instead of deriving the measurement from volume flow, there is consequently no need to compensate for pressure or temperature as would be the case with other gas flow measuring principles like differential pressure, turbine, positive displacement and vortex shedding.

If you search longer, you might even come up with an explanation of why thermal mass flowmeters measure mass "directly." The layman's explanation:

> *"Thermal dispersion mass flowmeters measure the heat convectively transferred from the heated velocity sensor to the gas molecules passing through the viscous boundary layer surrounding the sensor's heated cylindrical surface. Since the molecules bear the mass of the gas, thermal dispersion flowmeters directly measure mass flow rate."* [2]

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[1] https://sagemetering.com/knowledge-base/topics/fundamentals-of-thermal-mass-flow-measurement-2/#Why_are_pressure_and_temperature_correction_not_required (accessed on 19 June 2020)

[2] Olin, John G. (2008). "A Standard for Users and Manufacturers of Thermal Dispersion Mass Flow Meters," Sierra Instruments, Inc., p. 13.

(Of course, this leaves out the whole thermodynamic explanation, but at least ties the heat transfer to the mass of molecules.)

If you search even further, you may find a theoretical explanation like the following that proves the direct mass measurement using a theoretical explanation with formulas:

> *"The primary desired output variable is the total mass flow rate* q_m *flowing through conduit or flow body.* q_m *depends on the product* ρV*, the fluid's mass density times the point velocity, embodied in the Reynolds number* $Re = \rho VD/\mu \cdot \rho V$ *is often called the 'mass velocity' and is the total mass flow rate per unit area* $(kg/s \cdot m^2)$*."* [3]

As the above explanation suggests – because one is actually solving for the product, ρV, which is contained in the Reynolds number, by equating it to other known terms in an empirical correlation – density itself is not a required term to solve for this product. Therefore, density does not have an influence on the solution of this product, i.e. the mass velocity, which is being sought. Ergo, thermal mass measurement is not affected by density, and by matter of consequence, it is not affected by pressure and temperature.

However, when you continue searching the internet for thermal mass flowmeter suppliers you will come across statements such as, *"Our meters are temperature-compensated,"* or you might even happen upon some suppliers who offer a "pressure measurement" option. If you read further, you may find out that this pressure measurement option is also intended for compensating for changes in pressure. Now, you may already be asking yourself: *"I thought that thermal mass flowmeters are pressure and temperature independent?"*

Well, the truth is that this statement is only half of the truth. Thermal mass flowmeters are not dependent on density for the direct measurement of mass flow due to the reasons already stated above. However, they are greatly dependent on the fluid characteristics, which are in turn dependent on the gas composition, and the fluid characteristics (thermal conductivity [λ], specific heat capacity [c_p] and dynamic viscosity [μ]) are all influenced by changes in pressure and temperature. As soon as the application conditions vary from the reference conditions (those laboratory conditions existing during calibration), then, without temperature and pressure compensation, there are additional measurement errors that must be considered. So, to say that thermal mass flowmeters do not require pressure and temperature compensation is an untruth. They do require it, and practically every thermal mass flowmeter manufacturer uses some form of compensation to do this.

Temperature has typically a much larger influence on the fluid characteristics than pressure does. Because the entire measuring principle is based upon temperature measurement, a dynamic correction of this is possible. Pressure usually has a lesser influence on the fluid characteristics, and typically a fixed pressure value is entered into the device during commissioning. If the process pressure changes, the fixed value in the device does not change with it. In effect, these devices are not corrected for changes in pressure.

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[3] Olin, John G. (2008). "A Standard for Users and Manufacturers of Thermal Dispersion Mass Flow Meters," Sierra Instruments, Inc., p. 17.

Some devices like the t-mass 300/500 allow for an input reading from a separately installed pressure transmitter. This enables a dynamic compensation for changes in pressure. However, when would such a compensation be necessary? Obviously, this requires a pressure measuring point, which may not always be available, and either a current input or bus communication. In the end, this could result in an increased measuring point price for the customer, who is not always prepared to accept this especially when there are uncertainties about the added benefits.

As stated, pressure has typically a lesser influence on gas characteristics than temperature. However, its influence is also gas-dependent and can be greater depending on the type of gas. Generally, we state that one can expect in air about ±0.25% o.r. additional error for every bar difference (in either direction) to the reference pressure (in this case, the static pressure entered into the device). On the other hand, certain gases like CO_2 have a much larger dependency on the pressure, and this additional error can be much higher.

Following is a table with typical application gases that can be found in the Gas Engine:

	Essential gas characteristics and the theoretical additional error per bar pressure difference to the reference pressure										
Gas	**Thermal conductivity (λ) [W/mK] (20 °C, 5 bar)**	**Thermal conductivity (λ) [W/mK] (20 °C, 10 bar)**	**Thermal conductivity (λ) [W/mK] Variation (%)**	**Specific heat capacity (c_p) [J/kgK] (20 °C, 5 bar)**	**Specific heat capacity (c_p) [J/kgK] (20 °C, 10 bar)**	**Specific heat capacity (c_p) [J/kgK] Variation (%)**	**Dynamic viscosity (η) [Pas] (20 °C, 5 bar)**	**Dynamic viscosity (η) [Pas] (20 °C, 10 bar)**	**Dynamic viscosity (η) [Pas] Variation (%)**	**Add. error per 5 bar Δp (%)**	**Add. error per 1 bar Δp (%)**
Air	0.02581	0.02603	0.9%	1013.1	1021.5	0.8%	0.0000184	0.0000185	0.5%	1.25%	0.25%
Ar	0.01763	0.0178	1.0%	526.6	532.9	1.2%	0.0000225	0.0000226	0.4%	1.49%	0.30%
CO_2	0.01676	0.01706	1.8%	876.9	923.1	5.3%	0.0000148	0.000015	1.4%	4.24%	0.85%
H_2	0.1838	0.1841	0.2%	14286.4	14297.9	0.1%	0.0000089	0.0000089	0.0%	0.22%	0.04%
He	0.1534	0.1536	0.1%	5193.1	5193.5	0.0%	0.0000197	0.0000197	0.0%	0.17%	0.03%
Nat. Gas[4]	0.0332	0.03359	1.2%	2167	2200.8	1.6%	0.0000111	0.0000112	0.9%	1.87%	0.37%
N_2	0.02542	0.02562	0.8%	1047.1	1055.4	0.8%	0.0000177	0.0000178	0.6%	1.17%	0.23%
O_2	0.02581	0.026	0.7%	925.1	933.5	0.9%	0.0000203	0.0000204	0.5%	1.14%	0.23%
O_3	0.01275	0.01311	2.8%	859	889.8	3.6%	0.0000134	0.0000136	1.5%	4.41%	0.88%

The extent of influence of these gas characteristics on the mass flow accuracy follows in the order of magnitude: a) thermal conductivity (factor of 1.3); b) specific heat capacity (factor of 2/3) and c) viscosity (factor of 1/3). As can be seen by comparing the amount of change in these characteristics between certain gases, the change of gas characteristics has a clear relationship with the proportion of theoretical measuring error per bar of pressure change. Clearly, CO_2 and O_3 (shaded red) are considerably more influenced by changes in pressure than the other gases listed here. Therefore, it might behoove one to make more serious consideration of pressure compensation for these gases.

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[4] Natural gas with the following composition: 93% methane, 4% ethane, 2% nitrogen, 1% propane

Conclusion

Referring to this table can be helpful when deciding to use pressure compensation. Of course, this alone should not be the sole determinant when deciding for or against pressure compensation. Other important factors should be the amount of pressure fluctuation in the application. If the pressure is deemed to be fairly constant, using pressure compensation could be simply overkill. If, on the other hand, the pressure is known to be instable and to fluctuate in relatively large amounts, then it might be beneficial to use pressure compensation, especially in the case of gases like CO_2 whose gas characteristics are known to be more dependent upon pressure.

Also, t-mass has a velocity-dependent correction that is implemented at high flow velocities >70 m/s (>230 ft/s). As the effectiveness of this correction is also dependent upon the proximity of the specified process pressure in regard to the real process conditions, it is recommended in such cases to use dynamic pressure compensation to ensure that the pressure is as accurate as possible.

Lastly, the perhaps most important factor in deciding to use pressure compensation is to be candid about the importance of measuring accuracy and repeatability. Is a high level of measuring performance required for the application? Depending on the amount of pressure change, the corresponding measurement error might still be in an acceptable range for certain applications.

In the case of gas mixtures, it is recommended to consult with the Technical Expert Center at Endress+Hauser Flow. By providing them with details on your gas mixture – e.g. the gas composition in % volume, the process temperature and the minimum, maximum and nominal process pressures –, they can calculate the theoretical additional error for your specific gas mixture when the pressure varies between the extremes.