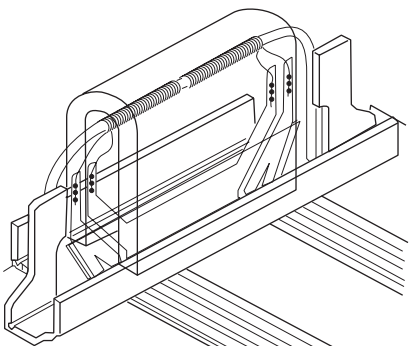


How the IsoSensor™ eliminates thermal siphoning

Technology Update

UNIT

Thermal siphoning in mass flow controllers (MFCs) can cause the calibration to shift. The IsoSensor eliminates thermal siphoning in mass flow controllers.



Unit thermal mass flow sensor, the IsoSensor

introduction

Thermal siphoning in mass flow controllers (MFCs) can cause the calibration to shift and the zero offset to change in ways that are difficult to predict. Thermal siphoning can affect all MFCs, but is more pronounced with high molecular weight gases and at higher pressures. This problem cannot be ignored and cannot be solved by simply rezeroing the output. It can, however, be completely removed with the correct design.

The following paper is an introduction to thermal siphoning. The material begins with the physical explanation of thermal siphoning, and discusses why it sometimes occurs in mass flow controllers. It describes those factors that enlarge or decrease the magnitude of thermal siphoning and concludes with the solution for preventing thermal siphoning in mass flow controllers.

free convection

Thermal siphoning is a continuous circulation of gas in a mass flow controller (MFC). Typically, thermal siphoning appears as an offset at zero when changing the mounting angle of the MFC. The offset is due to free convection, the movement of a fluid due to a difference in temperature.

When a fluid contacts a heated surface, energy is absorbed by the fluid. The energy causes the fluid to expand and the density of the fluid decreases. Under certain conditions, the decrease in density can cause the fluid to move.

For example, a fluid is placed in a closed container with the top surface heated as in Figure 1, Case A. The fluid near the top heats first. Heat slowly conducts towards the bottom. Since the hotter fluid expands more than the cooler fluid, a density gradient develops with the lightest on top and the heaviest on the bottom.

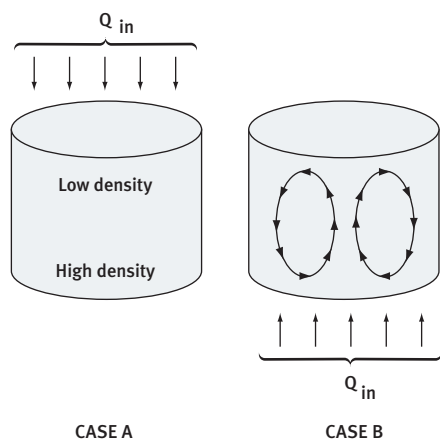


Figure 1. The location of the heat input will determine whether there is motion in the gas.

If, as in Case B, heat is applied at the lower surface, the density at the bottom decreases first. Gravity acts to force cooler, denser fluid to fall which in turn forces the hotter fluid to rise. This movement is called free convection and the forces are referred to as free convective or buoyancy forces. If the top surface is cool enough, convection cells develop as fluid continuously circulates. The fluid heats, rises, cools and falls.

thermal siphoning in an MFC

The flow path of an MFC is divided internally between the sensor tube and a bypass (Figure 2). A small portion of the flow is split off before entering the bypass region and directed into the sensor tube. The flow is rejoined immediately upstream of the control valve.

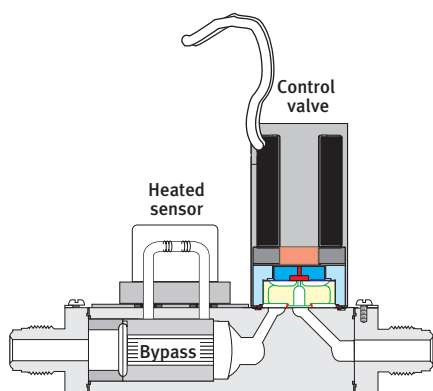


Figure 2. Typical MFC cutaway section of a flow controller

The basic principle behind the MFC is that the mass flow can be determined by the amount of heat the gas absorbs. This process of heating the gas is carried out in the sensor tube. To function most effectively, the gas is generally heated to at least 50°C above the ambient or room temperature.

The bypass temperature is close to ambient temperature. This thermal gradient between the sensor and the bypass is inherent in the design of every MFC.

Under normal operating conditions, when a pressure differential is applied to an MFC, gas will flow. The control valve in the MFC automatically adjusts its position so that actual flow through the unit is equal to the setpoint. When the external pressure gradient is removed or the control valve is closed, the MFC

should read zero flow. If the MFC is mounted in a horizontal position with the sensor tube on top and the control valve is closed, the MFC will read zero flow. Gas in the MFC heats only through conduction since the heat is applied with the sensor located on top of the bypass.

However, when the MFC is mounted vertically and the pressure differential across it is removed, the MFC does not read zero. Instead, the zero shifts depending on the density of the gas and mounting attitude. This zero shift is caused by free convective flow inside the MFC.

As the gas in the sensor tube heats up, its density decreases (Figure 3). The heated gas rises and flows out the top of the sensor tube where it contacts the bypass and cools. As the heated gas rises, cool gas is pulled into the lower end of the sensor tube and a continuous siphon is created. This gas circulation is seen as flow by the sensor and appears as a zero offset in the output of the MFC. The key issue is how to handle this offset.

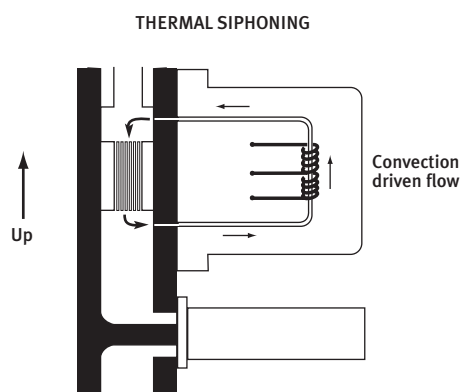


Figure 3. Thermal siphoning when mounted in vertical attitude

When a standard MFC is mounted as in Figure 2, no thermal siphoning is seen because the free convective forces sum to zero. By mounting the heater coils at the midpoint of the sensor, the temperature gradient is symmetric along the length of the sensor. The horizontal section generates no convective force and the convective forces generated by the two vertical legs cancel, so that the sum of the buoyancy forces is zero. When a standard MFC is rotated ninety degrees, the sensor legs no longer generate any convective forces, but the section with the heater coils does. Since the bypass is unheated, there is no convective opposition and thermal siphoning occurs.

parameters of thermal siphoning

To properly control the offset, it is important to understand which physical parameters affect thermal siphoning. Many factors are known to affect the magnitude of thermal siphoning. Through both theoretical and experimental methods these factors have been analyzed and have been divided into minor factors and major factors.

minor factors

Minor factors affecting the amount of thermal siphoning offset include the length of the sensor tube, the internal surface finish, the flow range of the MFC, the gas viscosity, the actual flow rate of the gas, and the sensitivity of the sensor. All minor factors linearly influence thermal siphoning. Since thermal siphoning is actual flow through the sensor tube, parameters that increase resistance to flow will decrease thermal siphoning. Increased sensor length, surface roughness, and gas viscosity all increase resistance to flow. Lower flow ranges, which have more restrictive bypasses also increase resistance to thermal siphon-

ing. Since convection is driven by differences in temperature, higher temperature differentials generate larger convective forces. The temperature differential is maximum at zero flow. As the flow rate increases, the average temperature of the gas in the sensor decreases. This means that the buoyancy forces which cause thermal siphoning are not constant, but decrease with increasing flow. The observed offset in MFC output caused by thermal siphoning can decrease significantly as gas begins to flow through the MFC.

major factors

Gas density, sensor diameter, and attitude of the MFC all have a significant influence on thermal siphoning. Gas density is dependent on gas pressure and molecular weight. Tests conducted at Celerity have shown thermal siphoning to increase with the square of the density. The data is listed in Table 1. and plotted in Figure 4. Heavy gases are very susceptible to thermal siphoning while nitrogen and other light gases are less susceptible.

Pressure (PSIG)	Standard sensor N ₂	CF ₄	SF ₆
0	-0.01	-1.4	-4.6
5	-0.05	-2.8	-9.1
10	-0.07	-4.5	-14.2
15	-1.0	-6.9	-21.0
20	-1.4	-9.2	-29.3
30	-2.2	-15.0	-49.1
40	-3.3	-22.9	-72.7

Table 1. Calibration drift due to thermal siphoning (% full scale)

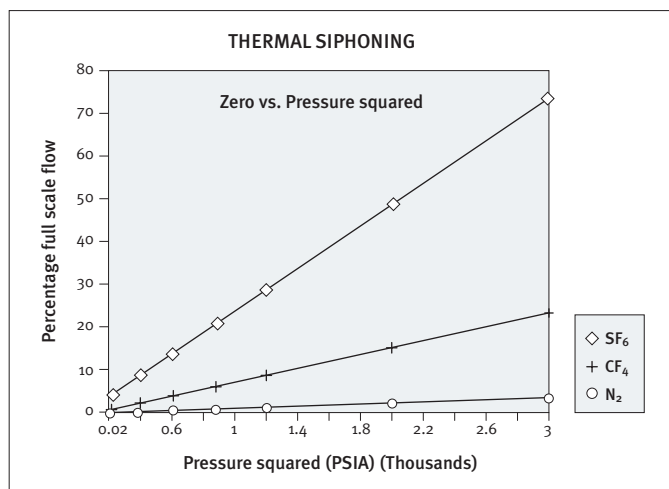


Figure 4. Thermal siphoning. Zero shift with the pressure squared.

Sensor diameter strongly influences thermal siphoning. As previously stated, the magnitude of the thermal siphoning is proportional to the resistance. But while resistance increases linearly with the length, it decreases with the fourth power of the radius. Doubling the radius reduces the resistance by sixteen times.

Only the attitude of the sensor can actually reduce thermal siphoning to zero without significantly altering the function of the MFC. Mounting the MFC either inlet up or inlet down maximizes free convection. Since the heated section of the sensor tube is vertical, gravitational forces are aligned with the flow. By rotating the heated section of the sensor tube perpendicular to the force of gravity, free convection can be set to zero.

the solution

These parameters point out the difficulty in handling the offset due to thermal siphoning. Since the value can be large and does not stay constant with flow rate, a simple electronic nulling of the convective term at zero flow is not adequate for most gases. Decreasing the diameter of the tube will reduce the convective flow, yet will also reduce the normal flow due to an increased pressure differential across the MFC. Therefore, the sensitivity of the sensor electronics must be increased, resulting in a magnification of the thermal siphoning term that we had initially sought to reduce. The proper solution is to drive only the buoyancy forces to zero.

Celerity has developed a flow sensor that sets the sum of the buoyancy terms to zero. The new sensor, designated the IsoSensor, and CrossFlow sensor mounting eliminates thermal siphoning in either vertical mounting position. (Figure 5)

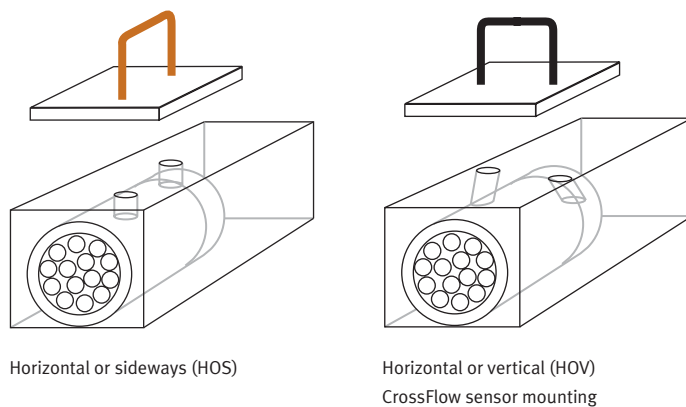


Figure 5. New IsoSensor with the CrossFlow sensor configuration cancels thermal siphoning in either vertical mounting attitude, vertical inlet up, or vertical inlet down.

the IsoSensor

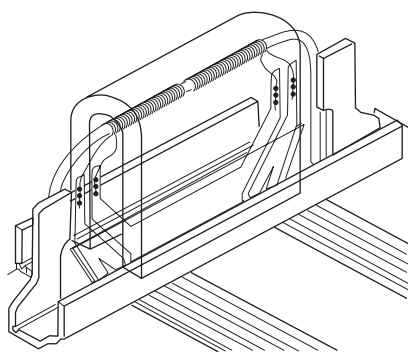


Figure 6. The IsoSensor

The IsoSensor was developed to be less complicated than previous thermal sensors by making it simple to manufacture, more rugged, and more stable. The IsoSensor's new design contains only seven parts versus twenty-one parts (Figure 6). The physical and thermal characteristics were optimized with a finite element model, producing a sensor that is easier to manufacture in volume with the highest quality.

The combination of a thin tube wall and a smaller bore sensor tube decreases the mounting attitude effects. Shorting the vertical sensor legs increased low-pressure sensitivity and mechanical stability.

Pressure (PSIG)	Standard sensor			"IsoSensor"		
	N ₂	CF ₄	SF ₆	N ₂	CF ₄	SF ₆
0	-0.01	-1.4	-4.6	0.0	0.0	0.0
5	-0.05	-2.8	-9.1	0.0	0.0	0.0
10	-0.07	-4.5	-14.2	0.0	0.0	0.0
15	-1.0	-6.9	-21.0	0.0	0.0	0.0
20	-1.4	-9.2	-29.3	0.0	0.0	0.0
30	-2.2	-15.0	-49.1	0.0	0.0	0.0
40	-3.3	-22.9	-72.7	0.0	0.0	-0.3

Table 2. Calibration shift due to thermal siphoning (% full scale).

A series of tests were conducted between a standard sensor and the IsoSensor mounted CrossFlow. The results are listed in Table 2. Thermal siphoning is eliminated. This translated to zero thermal siphoning for most gases. A small offset was noted for the most dense gas, SF₆, at the highest test pressure. Since thermal siphoning is a function of the square of the gas density multiplied by the gas pressure, for best results the gas supply pressure should be regulated to 20 psid or less. As a final note on application, the IsoSensor mounted CrossFlow is designed to eliminate thermal siphoning for a vertical mounting only, so check to see that the mass flow controller is properly mounted Figure 7.

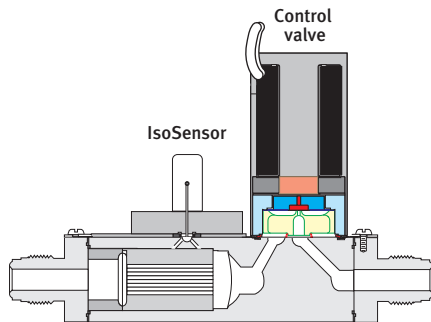


Figure 7. Proper mounting of the IsoSensor in the CrossFlow mounting configuration of a vertically mounted controller

in conclusion

Thermal siphoning is a convection driven phenomenon and is affected by both minor and major factors including gas density, resistance to flow, and the attitude of the flow sensor to gravitational forces. Ordinarily thermal siphoning cannot be electrically zeroed out since its magnitude changes with flow. The only way to completely eliminate thermal siphoning is to set free convective forces to zero. The IsoSensor sets the sum of the convective forces to zero so that mounting a Celerity's Unit mass flow controller vertically will not affect its accuracy or performance.