Factors Influencing Accuracy of Thermal Flow Sensors

Thermal flow sensors are indispensable tools used to gauge the flow rate of fluids (gases and liquids). Known for their ability to provide direct, accurate, and reliable flow measurements with seamless integration with flow channel and electronics, they are widely deployed in a myriad of industries. However, despite their robustness and utility, these sensors' performance can be influenced by several factors. This application note explores the various elements that can affect the accuracy of thermal mass flow sensors, from gas composition and ambient conditions to sensor aging and installation factors. Through a deeper understanding of these influencing factors, users can optimize sensor operation, enhancing the reliability and precision of their flow measurements.

Contents

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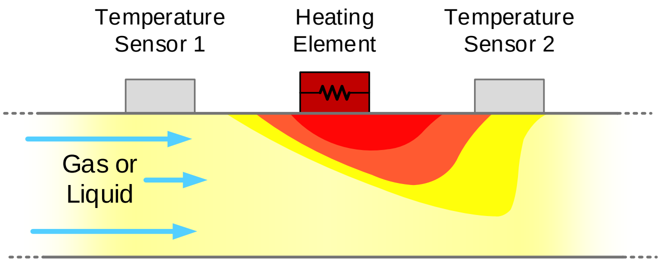
1. Operating Principle

Renesas' flow sensors are calorimetric Micro-Electro-Mechanical Systems (MEMS) thermal mass flow sensors that operate based on heat transfer principles. These innovative sensors function by micro-heating a gas or liquid medium and detecting the subsequent heat distribution across the sensor.

At the heart of these sensors lie two essential components: a micro-heater and two temperature sensors, or thermopiles. The role of the micro-heater is to generate a distinct heat profile within the medium. The two temperature sensors, positioned upstream and downstream of the heater, are then responsible for detecting this heat distribution. In conditions where no flow is present, the heat distribution remains symmetrical, and the temperature at both sensors remains equal.



When a fluid begins to flow across the sensor, however, this balance is disrupted. The flowing gas or liquid carries heat from the heater towards the downstream temperature sensor. As a result, the heat distribution shifts, creating a temperature disparity between the two sensors. The larger the fluid flow, the more significant this temperature difference becomes.

This operating principle is the same for Renesas' mass flow, air velocity, and liquid flow sensors. Even though the output unit for each type are mass, velocity, and volume respectively, it is only a matter of calibration and unit conversion depending on the fluid.

2. Factors Influencing Accuracy

The reported flow output will vary from expected when some factor causes the measurement condition to deviate from that of the operating principle. This section discusses the various factors that commonly arise.

2.1 Fluid Composition

Fluid composition plays a significant role in the thermal transfer properties of a gas or liquid, including its thermal conductivity, specific heat capacity, and thermal diffusivity. These properties are crucial for thermal mass flow sensors, which operate based on the principle of heat transfer. A change in fluid composition can significantly impact the sensor's measurements.

Thermal conductivity is a property that describes a substance's ability to conduct heat. Gases or liquids with high thermal conductivity are better at transferring heat than those with low thermal conductivity. Specific heat capacity is the amount of heat required to raise the temperature of a specific amount of a substance by a certain amount. Thermal diffusivity is a measure of how quickly a substance can transmit temperature changes, and it is a function of the substance's thermal conductivity, density, and specific heat capacity.

When a thermal mass flow sensor is calibrated, it is done for a specific fluid or fluid mix, accounting for that fluid's thermal transfer properties. If the fluid composition changes, the sensor's readings can be affected because the heat transfer properties have changed. Renesas' gas flow sensors are calibrated using N2 gas, while Renesas' liquid flow sensors are calibrated using water.

A different fluid composition from the base calibration fluid will result in off-scale sensor readings. A conversion factor may be multiplied to the sensor output as an approximation to convert the output for the fluid. Figure 1 shows examples of conversion factors for various gases.

Gas	Symbol	Conversion Factor
Air	- - -	1
Argon	Ar	1.39
Carbon Dioxide	CO_2	0.7
Ethane	C_2H_6	0.5
Helium	He	1.45
Hydrogen	H_2	1.01
Hydrogen Chloride	HCl	1
Nitric Oxide	NO	0.99
Nitrogen	N_2	1
Nitrous Oxide	N_2O	0.71
Oxygen	O_2	0.993
Propane	C_3H_8	0.36

Figure 1. Conversion Factors

2.2 Ambient Conditions

2.2.1. Temperature

The temperature of a fluid can significantly influence its thermal transfer properties. As with changes in fluid composition, changing temperature affects the fluid's thermal conductivity, specific heat capacity, and thermal diffusivity. In thermal flow sensors, changes in the fluid temperature can alter the heat transfer from the sensor's heated element to the fluid.

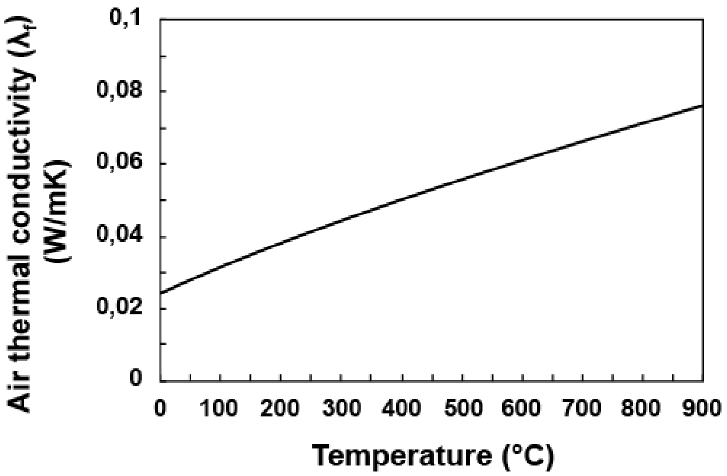


Figure 2. Air Temperature vs. Conductivity (GZ, 2019)

Renesas' calibrated flow sensors have a microcontroller that can apply a temperature correction factor based on the measured fluid temperature. This factor adjusts the sensor output to give an accurate flow rate despite changes in fluid temperature. However, this correction factor is based off of the fluid that the sensor was calibrated for.

Using the flow sensors on a different fluid may require replacing the correction factor or applying one post-output additionally.

2.2.2. Pressure

Pressure is another ambient condition that affects a fluid's thermal properties. In the example of air, pressure affects thermal conductivity in a much less linear fashion. The pressure to thermal conductivity curve for air is shaped like an S-curve, which fortunately means normal atmospheric pressure has limited effect on the sensor output.

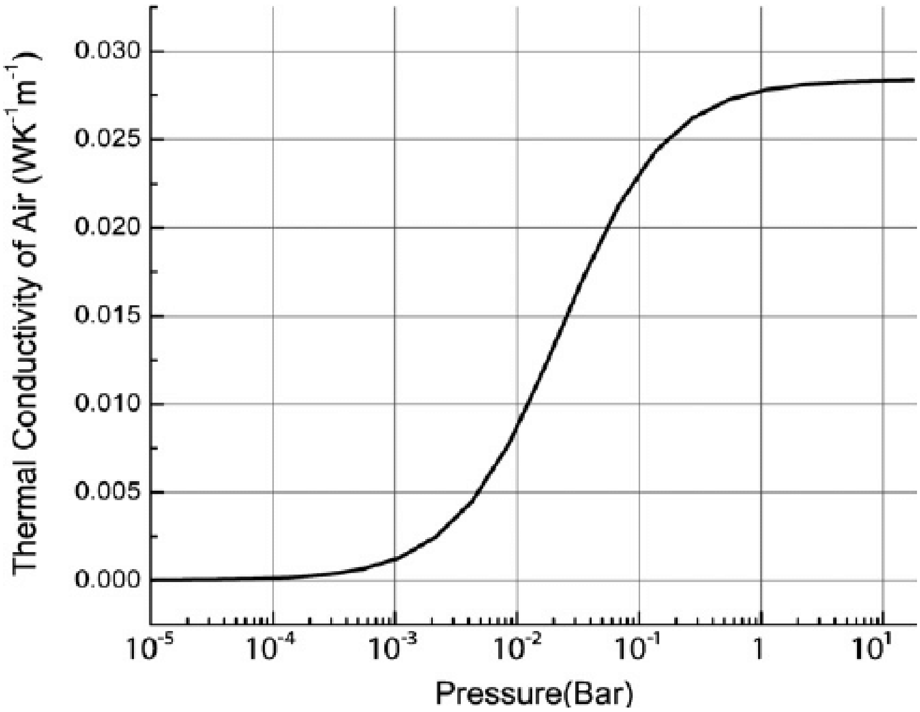


Figure 3. Air Pressure vs. Conductivity (Wu, 2009)

This makes intuitive sense as low density of gases at low pressure would mean less particle interaction for thermal transfer. Nevertheless, it is important to keep in mind that the effect of pressure is present and may present an issue at certain ranges for different fluids.

2.2.3. Humidity

Humidity is the third ambient condition factor that may affect flow readings. For this condition, the effect of humidity on thermal conductivity is strongly coupled with temperature. At low temperature ranges, conductivity is not very sensitive to humidity. However, a strong divergence in conductivity to humidity arises once temperature gets far from normal room temperature range.

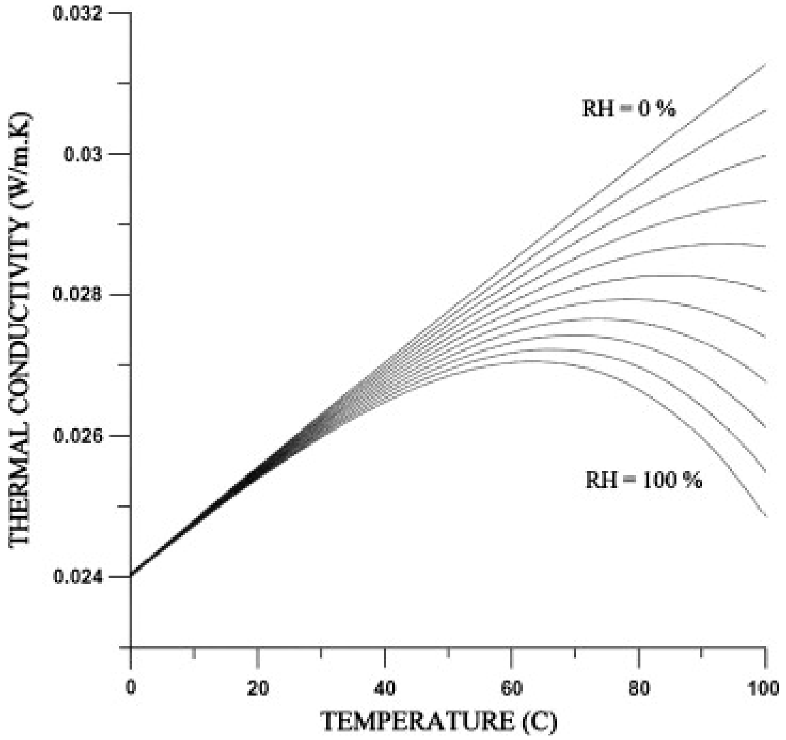


Figure 4. Air Humidity vs. Conductivity (Tsilingiris, 2008)

If the flow sensor is not used in a closed system, users should be aware of the humidity and temperature levels for the gases that they are measuring flow.

2.3 Flow Profiles

2.3.1. Types of Flow

Flow profile, or the way in which fluid moves through a pipe or duct, can indeed affect the accuracy of thermal mass flow sensors. There are two primary types of flow profiles: laminar and turbulent.

Laminar flow – the fluid moves smoothly in parallel layers. Here, the heat transfer from the sensor is more predictable and consistent, resulting in more accurate readings. It is important to note that the sensor should be positioned in the flow where it's fully developed (typically in the middle of the pipe) rather than near the walls to ensure that it is not in an area of lower velocity that could skew the readings.

Turbulent flow – consists of eddies and swirls, causing the fluid particles to move in a random and chaotic manner. While turbulent flow ensures a good mix of particles and heat, it introduces more variables and uncertainty into the heat transfer process from the sensor to the gas, which can impact the sensor's accuracy. A consistent flow path is desirable to ensure the flow conditions are match calibration conditions.

However, in practical applications, it's challenging to maintain purely laminar flow, especially at high flow rates or in large pipes. A combination of proper sensor placement, use of flow conditioning devices, and in some cases, mathematical models or algorithms to account for flow disturbances, can help achieve accurate readings even in less than ideal flow conditions.

2.3.2. Flow Conditioning

The sensor should be placed in a position where the flow profile is expected to be the most uniform. This typically means avoiding areas near bends, valves, or other features that can disrupt the flow. It is generally recommended to place the sensor in a straight section of the pipe, with a certain length of straight pipe upstream and downstream of the sensor.

Vibration can also introduce significant disturbances to the flow profile in a pipe, leading to pulsating flow, where the fluid's velocity fluctuates. This fluctuation can cause the flow to switch between laminar and turbulent states.

Flow conditioning elements such as straighteners or perforated plates can be used to minimize irregularities in the flow profile and produce a more uniform flow, particularly in turbulent conditions.

In some cases, especially for larger ducts or pipes, multiple sensors can be installed at different radial positions. The individual measurements can then be averaged to provide a more accurate representation of the total flow rate.

By understanding and appropriately managing the flow profile, users can achieve more accurate and reliable measurements with thermal mass flow sensors.

2.4 Contamination

The presence of contaminants can significantly affect the accuracy of thermal mass flow sensors by altering or interfering with fluid thermal transfer properties. These contaminants can range from dust and particulates to liquid droplets or chemical residues.

Dust or other small particles in the gas flow can accumulate on the sensor elements over time. This layer of dust effectively insulates the sensor, reducing its ability to transfer heat to the gas flow. As the heat transfer is directly used to measure the mass flow rate, any reduction in heat transfer can cause an underestimation of the actual flow rate, reducing the sensor's accuracy. Moreover, larger particles might cause physical damage to the sensor elements, which can further degrade the sensor performance or even cause it to fail entirely.

If the gas flow contains liquid droplets, they can also accumulate on the sensor elements, similar to dust. As most liquids have much higher thermal conductivities than gases, the presence of liquid on the sensor can significantly increase the heat transfer, leading to an overestimation of the mass flow rate. Furthermore, if the liquid freezes on the sensor, it can cause physical damage to the sensor elements, just like larger particles.

Some fluids might contain chemical compounds that can react with the sensor materials or deposit residues on the sensor elements. These residues can alter the sensor's thermal properties, affecting its heat transfer and thus its accuracy. In extreme cases, corrosive gases can cause significant degradation or failure of the sensor elements.

To mitigate the effects of contamination, several strategies can be employed. Filters may be applied to remove particles or droplets from the fluid flow before it reaches the sensor. Sensor elements may be equipped with protective coatings that can resist dust accumulation, liquid contact, or chemical attack. Lastly, regular cleaning of the sensor elements can help remove any accumulated contaminants.

3. References

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Revision History

Revision	Date	Description
1.00	Jun 26, 2023	Initial release.

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