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Dual Sensor Setup for Thermal Mass Flow Sensor Diagnostics

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Abstract

For the flow measurement of gaseous flows thermal mass flow sensors are commonly used. They are based on a heat transfer measurement from a heated sensor into the fluid and provide precise mass flow measurements independent of the gas pressure. A critical issue for thermal mass flow sensors is the formation of coatings on the sensor head as they often occur in harsh environments. A coating will change the thermal properties of the sensor and will thus strongly influence the flow measurement. An accurate and stable measurement is therefore difficult to provide under harsh conditions.

In this study possibilities are thus investigated to detect the presence of coatings on the sensor head by using a dual temperature sensor setup. Here the thermal behavior of the sensor is investigated and models are derived for describing the sensor and the influence of coatings. Based on these models algorithms are developed to provide coating diagnostics for thermal mass flow sensors.

Introduction

Thermal mass flow meters, as shown in Figure 1, are widely used for measuring the mass flow of gasous media. They have many applications in industrial flow measurement and especially in the process industry to measure the different gaseous flows with high precision. The sensors are based on the cooling effect of a fluid flow around a heated surface. The devices measure directly the mass flow around the sensor element without the need for an additional pressure correction and they are thus well suited for gas flow measurements.


Figure 1: Thermal mass flow sensor device and sensor head. [1]

Any changes to the thermal properties of the sensor element can strongly change the measurement performance of these devices. Especially in harsh environments as in the process industries coatings can form on top of the sensor element and will change the thermal contact between the sensor and the fluid. An insulation of the senor element will reduce the cooling effect of the surrounding fluid flow which directly results in a wrong flow measurement. The formation of coatings is therefore a critical issue for the accuracy of thermal mass flow sensors. Already thin oil and polymer coatings can strongly influence the measurement accuracy as shown in Figure 2 [2]. The here shown effect of thin coating layers generates measurement errors which are far outside the required accuracy for standard flow meters.

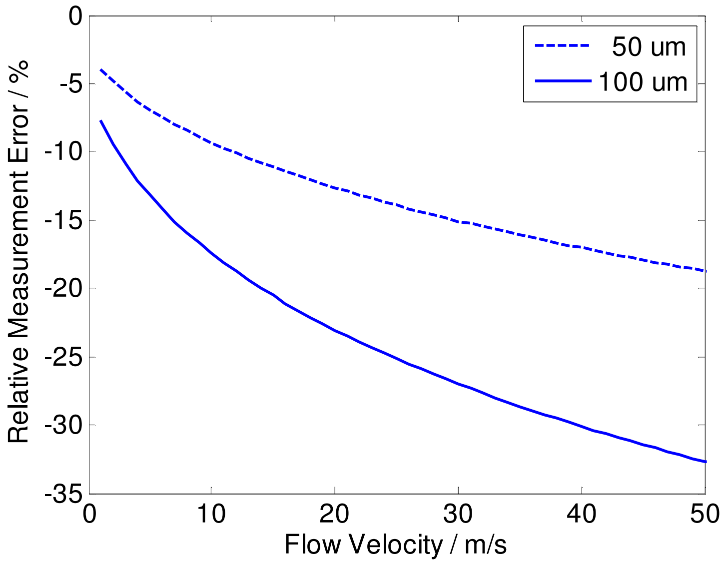

Figure 2: Measurement error generated by a thin oil layer on the sensor head. [2]

Different diagnostic methods have thus already been investigated for detecting such coatings on a thermal mass flow sensor. Deane and McQueen [3] proposed the use of a reference sensor, where the normal operation with the standard flow sensor is stopped and an additional sensor is heated up for a flow measurement. Both sensors are calibrated and in case a fouling on one sensor occurs the readings of the two sensors are different. This diagnosis needs an interuption of the flow measurement for switching the sensors and thus may not applicable for all applications.

An alternative method was investigated by Schrag et al. [4] and Pape et al. [2]. Here an AC signal is overlayed onto the DC signal or slow varying signal for the flow measurement. The DC signal is mostly affected by the static heat properties of the sensor, the heat transfer and the heat conductivity, whereas the AC signal depends strongly on the dynamic thermal properties such as the heat capacity of the sensor. A coating of the sensor will also result in a change of the heat capacity and thus the coating of the sensor can be measured. The method will deliver a continuous coating measurement. But a higher effort is needed to implement this method into the device, to supply the AC signals onto the sensor and for the later evaluation.

The goal of this study is thus the investigation of a simple detection method which can easily be implemented into a standard thermal mass flow meter by using additional temperature sensors in the sensor head. Such additional temperature sensors can be repeatedly found already in thermal flow sensors. Or when using film resistors for the temperature measurement, additional conductor can easily be printed onto the chip and a temperature sensor chip with two or more temperature sensors can be realized. The difficulties are here to derive a detection method which can distinguish the influences of the different sensor parameters, especially the effect of the flow velocity and the coating on the measurement signal. This will be investigated in more detail in the following.

Nomenclature

Latin letters

A	W / K	Constant of King's Law
B	N m^3 / (kg K)	Constant of King's Law
c	J / (kg K)	Specific heat capacity

CP		Coating parameter ($CP = l/(TI\,\lambda \ln(T_H / T_S))$)
d	m	Thickness of sensor head
F	m^2	Area/Cross Section
l	m	Distance between heater and additional temperature sensor
L	m	Characteristic length of sensor
n		Exponent of King's Law
P	W	Power
Re		Reynolds number ($\mathrm{Re} = \rho\, v\, L/\eta$)
T	K	Temperature
TI	K / W	Thermal impedance ($TI = \Delta T/P$)
U	m	Perimeter
v	m / s	Fluid velocity
x	m	Spatial coordinate

Greek Letters:

α	W/(m^2 K)	Heat transfer coefficient
λ	W / (m K)	Heat conductivity
η	Pa s	Dynamic viscosity
ρ	kg / m^3	Density

Indizes

H	Heater
S	Additional temperature sensor
un	uncoated

Basics

Thermal mass flow sensors commonly consists of two temperature sensors which are thermally independent as e.g. shown in Figure 1. One temperature sensor is used for measuring the fluid temperature. The other temperature sensor is heated to a certain temperature above the fluid temperature and the temperature difference between the sensor and the fluid ΔT as well as the applied power P is measured. The ratio between the temperature difference and the applied power $\Delta T/P$ is then used as measurement value to determine the mass flow $\rho\, v$ around the sensor. This ratio is also called the thermal impedance $TI = \Delta T/P$. The relation between the thermal impedance and the mass flow $\rho\, v$ for determining the flow rate is often described by King's law [5]:

$$\frac{P}{\Delta T} = TI^{-1} = A + B\,\mathrm{Re}^n \tag{1}$$

where $\mathrm{Re} = \rho\, v\, L/\eta$ is the Reynolds number, describing the flow around the sensor, L is a typical length of the sensor head in the direction of flow and η the fluid viscosity. n is a constant with a typical value of n=0.5 and A and B are two sensor specific constants, which are normally determined during the calibration.

The King's law is a correlation derived for hot-wire anemometer but appplies quite well for many thermal mass flow sensors. The first term of equation (1) (proportional to A) describes the heat losses as e.g. the heat flux into the holder and the second term (proportional to B) is related to the heat flux from the sensor to the fluid flow. The second term is thus the most relevant term and should dominate the equation. A coating would change the heat flux from the sensor into the fluid and would thus change the constant B. This change results in a different thermal impedance reading and thus a measurement error as shown in Figure 2. But a change of B due to the coating will have a similar impact on the thermal impedance as a change of the flow rate, which changes the value of Re. By just measuring the applied power and the temperature difference these two effects can thus not be distinguish and the error due to the coating can not be detected out of these information.

But the coating will also change the heat conduction into the sensor holder and thus a change of the heat losses as described by the first term is to be expected. Therefore, the temperature distribution along the sensor will change as the balance of heat conduction and heat loss is changed and a temperature sensor in some distance from the heated temperature sensor will thus see a different temperature. For a coating detection thus an additional temperature sensor could be included into the sensor head some distance appart from the original sensor. In Figure 3 an example of the top most part of such a sensor head is given. The heater T_H will be at the top of the plate. It will be heated up to a certain temperature and measures the flow rate around the sensor. In a distance l to this heater an additional temperature sensor is integrated into the plate which is used for measuring changes of the temperature profile.

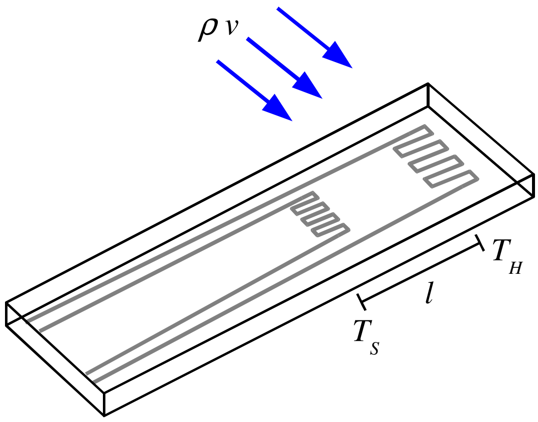

Figure 3: Sketch of a sensor head with additional temperature sensor.

Equation (1) is only a global description of the heat fluxes in the thermal mass flow sensor. For a better understanding of the coating induced temperature changes at different locations a local description is needed for the heat fluxes and temperature distribution inside the sensor. Therefore, a more detailed model based on this sensor setup will be developed here.

At the surface of the sensor we will have a heat transfer α induced by the mass flow. The heat transfer coefficient is a function of the flow around the sensor [5]

$$\alpha(\rho v) \sim \mathrm{Re}^n \tag{2}$$

where the exact form of this equation depends on the kind of flow and the outside geometry of the sensor. The heat transfer inside the sensor is then described by the time independent heat conduction equation

$$-\lambda \nabla^2 T(\vec{x}) = \dot{q}(\vec{x}) \tag{3}$$

with the thermal conductivity λ and $\dot{q}(\vec{x})$ the power density inside the sensor head which is for a punctual heater at the position x_0 given by $\dot{q}(\vec{x}) = P\,\delta(x_0)$. For a complex geometry we will get a three-dimensional temperature distribution and we have to solve equation (3) numerical, for example by using a finite element approach. In Figure 4 this is done for a flat sensor head geometry.

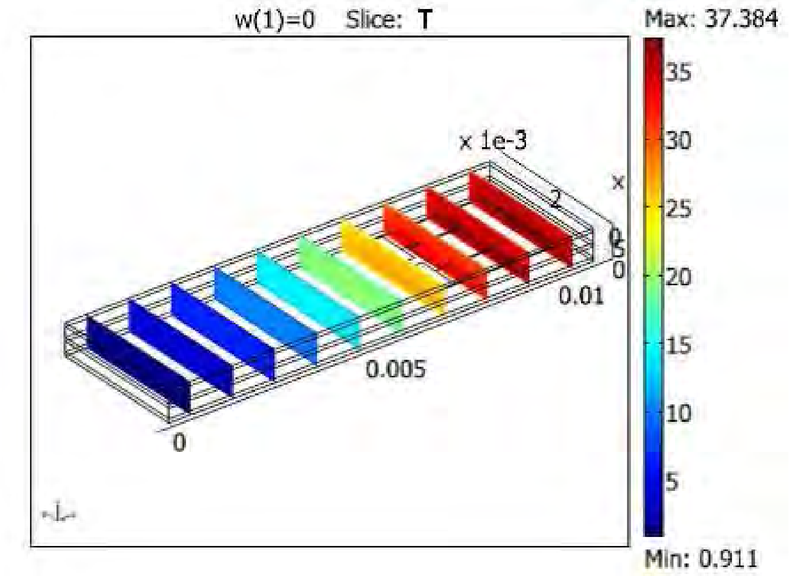

Figure 4: Simulated temperature distribution inside a thermal mass flow sensor head.

Here the sensor head is heated in the right part by a heating element covering nearly the full width of the sensor. Close to the heater we will have the highest temperature which will continuously drop with the distance to the heater. This temperature drop will be changed by a coating on top of the sensor.

This three-dimensional calculation is not suited for deriving a coating detection algorithm in a practical thermal mass flow sensor. Here a simplified model is needed. As it can also be seen in Figure 4 for a heater covering a main part of the sensor width, the temperature distribution is quite uniform in the directions perpendicular to the direction of the holder. Thus for such sensor head setups, which are quite common, we can assume a one-dimensional temperature distribution inside the sensor head. The sensor will thus be described by a one-dimensional model as shown in Figure 5. The sensor head is assumed here as a flat, semiinfinite plate with the heater at x=0, which heats up to a temperatur T_H at the heater position and an infinite extension in the positive x-direction. At the position $x=l$ we will have an additional temperature sensor T_S. For simplificity the fluid temperature has been assumed to be zero and thus T expresses directly the temperature difference between sensor and fluid temperature.

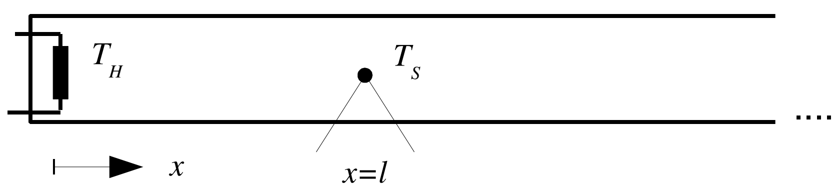

Figure 5: Simplified model with an additional temperature sensor.

Equation (3) can then be simplified to:

$$-\lambda \frac{\partial T}{\partial x} = \dot{q} = \alpha \frac{U}{F}. \tag{4}$$

with the boundary conditions:

$$\begin{aligned} x = 0: &\quad -\lambda \frac{\partial T}{\partial x} = \frac{P}{F} \\ x \to \infty: &\quad T = 0 \end{aligned} \tag{5}$$

The heat losses due to the heat transfer at the outside of the sensor have been included in the one-dimensional equation as a heat sink $\dot{q} = \alpha U / F$. F is here the cross section and U the perimeter of the sensor head.

Equation (4) with the boundary conditions (5) will be solved by the following equation:

$$T(x) = T_H \, e^{-\sqrt{\frac{\alpha U}{\lambda F}} x} \tag{6}$$

where T_H is the temperature of the heater at the position $x=0$. Out of the boundary condition (5) the applied power and the heater are here related by $P = T_H \, A \sqrt{F/(\alpha\lambda U)}$.

We will thus get an exponential temperature drop along the sensor axis, where the temperature drop is determined by the external heat transfer at the outside of the sensor head, the heat conductivity, cross section and perimeter of the sensor head.The temperature drop and thus the temperature at the position $x=l$ of the additional temperature sensor will be therefore directly influenced by a coating of the sensor head. The coating will change the head conductivity λ and the sensor thickness d and a coating detection should thus be possible by measuring the temperatures T_H at the heater and T_S at the additional temperature sensor position.

Coating Detection

Equation (6) shows the dependency of the additional temperature measurement on the thickness and heat conductivity of the sensor head and thus the possibility to detect a coating on the sensor head by considering the two temperatures. For a sensor with a thickness of d=0.6mm and a distance between heater and additional temperature sensor of l=2mm the two temperatures have been calculated for different flow velocities around the sensor and oil coatings with different thicknesses. The ratio T_H/T_S of these two temperatures is shown in Figure 6.

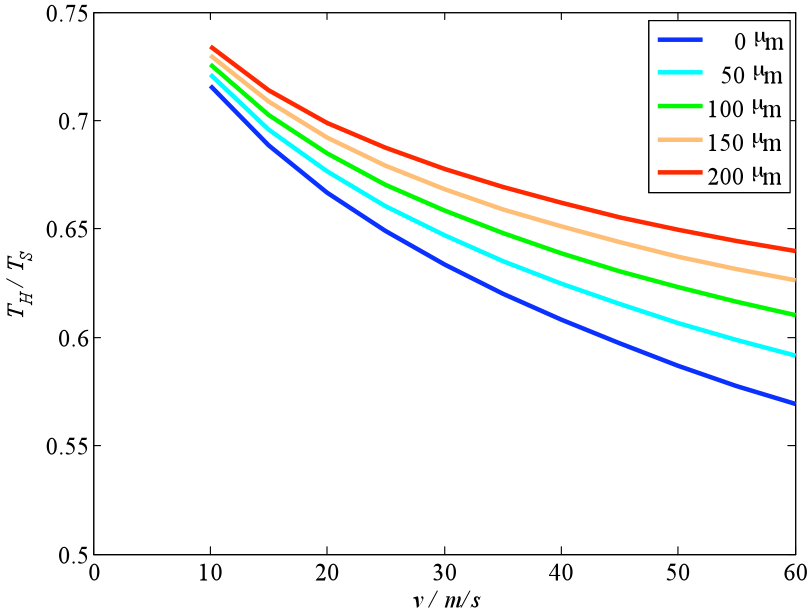

Figure 6: Temperature relation between heater and additional temperature sensor for a flat sensor head coated with an oil film for different flow velocities and film thicknesses.

As can be seen, the temperature at the additional sensor will increase with a raising coating thickness. Here the additional material allows a higher heat flux from the heater into the sensor head and thus a higher temperature is reached at the additional temperature sensor. But additionally the relation is also influenced by a change of the flow velocity around the sensor head, which will superimpose with the effect of the sensor coating. This can also be seen from equation 6, where the temperature drop is determined by the sensor head thickness and heat conductivity as well as the heat transfer α on the outside which occur only in the combination $\alpha U/(\lambda F)$.

The temperature relations thus depends on the coating and the flow velocity and during the operation of this sensor the flow velocity and the coating can not be determined independently with these information.

The main challenge for the coating detection method is thus to find a parameter to distinguish between the two effects of the flow velocity and the coating.

As additional information we can take also the applied power into account. The power was given as

$$\frac{P}{A} = T_H \sqrt{\frac{\alpha \lambda U}{A}} \qquad \rightarrow \qquad \sqrt{\alpha} = \frac{P}{T_H A}\sqrt{\frac{A}{\lambda U}} = \frac{1}{TI\,A}\sqrt{\frac{A}{\lambda U}} \tag{7}$$

with TI as thermal impedance $TI = T_H / P$. Inserting this expression into equation (6) we can rewrite equation (6) to

$$\lambda A = \frac{l}{TI \ln(T_H / T_S)} \tag{8}$$

which will give an expression for the heat flux along the sensor head and thus the effective heat conductivity in the sensor head considering the conduction in the sensor head material and in the coating.

Applying a coating onto the sensor will change this effective heat conductivity and the coating could be detected by this change. The main advantage of this expression is its independency of the heat transfer coefficient α and thus the flow velocity around the sensor v. The effective heat conductivity can be expressed just by the thermal impedance and the relation between the two temperature measurements.

For detecting the thermal conductivity change it is more convenient to compare the effective thermal conductivity to the thermal conductivity in the uncoated case $A_{un}\ \lambda_{un}$. Here we will get a dimensionless parameter, the “coating parameter” CP:

$$CP = \frac{\lambda A}{\lambda_{un} A_{un}} = \frac{l}{TI\, A_{un}\, \lambda_{un} \ln(T_H / T_S)} \tag{9}$$

This parameter will indicate the state of the coating. For the uncoated, non aged sensor it will be one and when a coating is found on the sensor it is expected to raise due to the additional material, depending on the relation between the thermal conductivity of the coating and of the sensor head. Also an errosion on the sensor head due to aggressive media could be seen by a reduction of this factor to values below one.

This factor has been derived for a simplified model of a thermal mass flow sensor. But for short distances compared to the overall dimensions of the sensor, as they are to be expected when applying an additional sensor on the chip of the sensor head, the conditions on the sensor head are often quite close to the here made assumptions and thus this factor will still be a valid value for the coating detection. In case of strong deviations from this model assumption, the relationship between the temperature ratio and the thermal impedance have to be adapted. Here addititions to the model, as e.g. to take the finite length of the sensor head into account or by considering the temperature distribution in the vertical directions, could help in adapting to these geometries.

Comparison with Simulations

The coating parameter CP in equation (9), based on a simplified model, will be compared here with simulations of a more complex sensor head. For the comparison the sensor head has been chosen as the one used in Figure 6. The distance between heater and additional temperature sensor is in this case 2mm and oil coatings between 0 and 200μm have been simulated for different flow velocities using an inhouse simulation code.

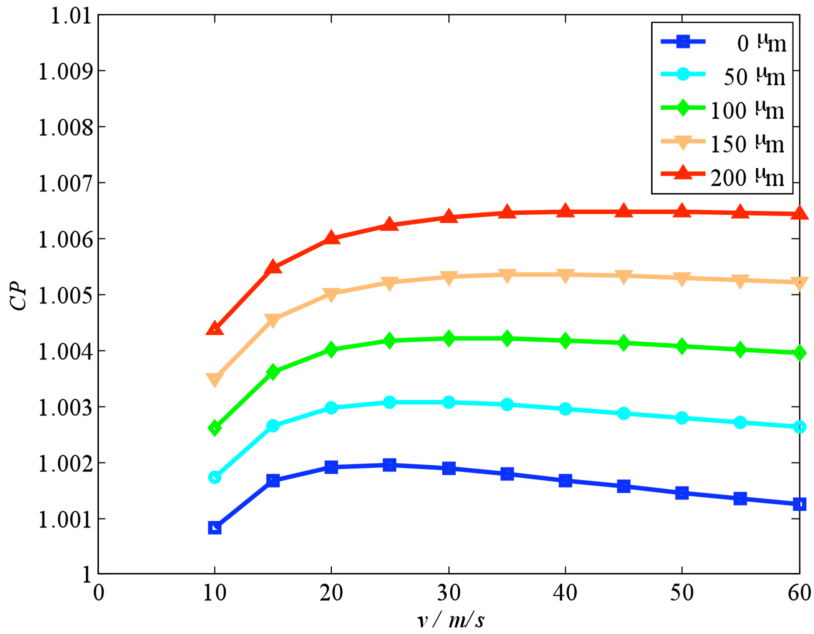

Figure 7: Coating parameter for a flat sensor head coated with an oil film for different flow velocities and film thicknesses.

In Figure 7 the coating parameter for this simulated temperature distributions is shown. Here we can see that there is a strong deviation with different coating thicknesses. The coating provides an additional heat flux through the sensor head and thus raises the effective thermal conductivity, even when the thermal conductivity of the coating is much lower than the thermal conductivity of the sensor material. The dependency on the flow velocity is instead quite low, only for lower flow velocities a higher dependency is found. This deviations arise due to the more complex sensor geometry which do not fully fulfill the assumption made for the model. Also the coating parameter for the uncoated sensor is slightly higher than one due to the non ideal conditions. For the coating detection these effects could be taken into account by a rough calibration of the sensor or by evaluating the coating detection only at certain velocities.

Conclusions

Coating on a thermal mass flow sensor head can strongly influence the flow measurement of this device and generates errors far from the expected error limits. The coating affects the sensor reading in a similar manner as changes of the flow rate around the sensor and it is thus very difficult to distinguish these two effects even with an additional sensor. The main challenge for a coating detection is to find a sensor parameter for the detection which will not be influenced by the flow velocity and thus an independent detection is possible. Here based on a simple model a coating parameter has been developed, which is independent on the flow rate and will directly indicate a change due to coatings. Although the parameter has been developed from a simple model, it can be also applied to more complex geometries as it has been shown by comparison with simulations on a certain sensor geometry. For geometries strongly differ from the here made assumption the parameter can be used as base and can be adapted to fit to more complex models.

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