THE TWO SENSOR μ-FLOWN
AN IMPROVED FLOW SENSING PRINCIPLE

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A novel flow sensing principle will be presented which combines the advantages of both the anemometer and the mass flow sensor. The sensor consists of two elements which are used as both sensor and heater. For small flows a qualitative model of sensitivity and frequency response as well as measurements will be presented.

INTRODUCTION

Flow sensors commonly are used in, for example, micro liquid handling systems or for measuring gas flows. One example is a gas flow sensor used as a microphone: the Microflown [3]. This sensor is designed to measure particle velocity, very small flows in a frequency range up to twenty kilo Hertz. While the signal to noise ratio is a very important parameter of the microflown an innovative measuring principle is optimised with respect to the signal to noise ratio.

To measure small air flows, mass flow sensors (MFS) are commonly used. This type of sensor consists of a heater and two temperature sensors equally spaced around this heater. The flow alters the temperature distribution around the heater. This is measured by the sensors and the temperature difference quantifies the flow.

Another principle to measure a flow is an anemometer. This sensor consists of one heated wire which acts like a sensor at the same time. The heat loss, which is dependent on the air flow, is measured.

A disadvantage of the anemometer is the low sensitivity for small DC flows [1]. The direction of the flow can not be obtained while for both positive and negative flows the heat loss is the same.

The new proposed sensor, the Two Sensor Microflown (TSM), consists of two heated elements which are used as both sensor and heater (like the anemometer) and uses the differential temperature as a representation of the flow (like the MFS). Using only hot sensors (and no heater) will lead to an easier to make sensor, an improved signal to noise ratio and a larger dynamic range, as will be shown in this article.

THE MODEL OF THE TWO SENSOR MICROFLOWN

First only one heated wire will be observed. This wire is heated by an electrical current. At the same time the electrical resistance of this wire is measured to determine the temperature. When a flow is applied, the temperature of the wire will drop because the convective heat loss increases. This effect can be described by observing the heat balance for a hot wire (Fig. 1).

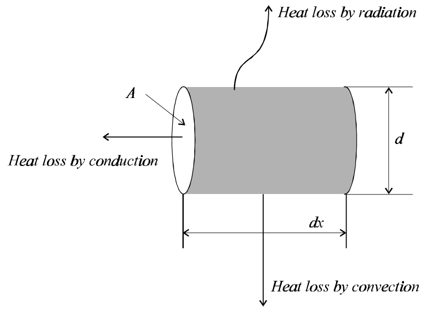

Fig. 1: The various heat losses of a hot wire.

Heat is generated electrically in the wire and lost not only by convection to the fluid but also by conduction to the bulk and radiation to the surroundings. In addition, there is heat storage in the wire. An energy balance yields for the following differential equation for the heat balance in a hot wire sensor (eq. 1):

$$A\frac{\partial}{\partial x}\left(k_s\frac{\partial T_s}{\partial x}\right)+\frac{I^2 r_r}{A}-rcA\frac{\partial T_s}{\partial t}-pdh(T_s-T_f)-pdse(T_s^4-T_{sur}^4)=0$$

Here k_S is the coefficient of thermal conductivity for the sensor material, T_S the sensor temperature, I the electrical current, r_r the resistivity of the sensor material, r the density of the sensor material, c the specific heat, t the time, h the coefficient of convective heat transfer, T_f the temperature of the fluid, s the Stefan-Boltzmann constant, e the emissivity of the sensor and T_{sur} the temperature of the surroundings. The first part of eq. 1 represents the heat transfer by conduction in the wire, the second part the electrical heat generation, the third part the heat storage, the fourth the convection loss and the last part the emission loss. The last part is normally neglected while the emission loss is assumed very small [5].

In order to develop an expression for the frequency response of a heated wire sensor the heat balance is used. If the sensor is assumed long enough (i.e. a high aspect ratio) for the temperature profile to be constant and the heat loss by radiation is neglected, eq. 1 will be:

$$\frac{I^2 \rho_r}{A} = \rho c A \frac{\partial T_s}{\partial t} + \pi d h (T_s - T_f) \qquad (2)$$

The coefficient of convective heat transfer is given by [1]:

$$h = A + B\sqrt{U} \qquad (3)$$

A and B are arbitrary constants and U represents the fluid velocity. For a cylinder shaped wire these constants are known as:

$$A + B\sqrt{U} = \frac{k_f}{d}\left(0.42\left(\frac{\nu}{\alpha_d}\right)^{0.2} + 0.57\left(\frac{\nu}{\alpha_d}\right)^{0.33}\sqrt{\frac{Ud}{\nu}}\right) \qquad (4)$$

Using k_f as the coefficient of thermal conductivity of the fluid, ν the kinematic viscosity of the fluid and α_d the thermal diffusivity of the fluid. If the DC flow is small (smaller than 0.2 m/s in air [7]) the first term between the brackets becomes dominant and therefore sensitivity decreases. While for positive and negative flows the heat loss is the same an AC flow can only be measured with a DC bias flow [8].

The value of a resistor is given by:

$$R = \frac{\rho_r l}{A} \qquad (5)$$

And the dependence of the temperature is given by:

$$R_s = R_f + \alpha (T_s - T_f) R_f \qquad (6)$$

Using α as the first order temperature coefficient of resistivity, T_f as a certain reference temperature (in this case the fluid temperature) and R_f as the resistance of the resistor at the reference temperature. Substituting the previous relations the following relation yields:

$$I^2 R_s = P = \frac{\rho c A l}{\alpha R_f}\frac{\partial R_s}{\partial t} + \frac{\pi d}{\alpha R_0}(A + B\sqrt{U})(R_s - R_f) \qquad (7)$$

If now is assumed that all fluctuating quantities can be expressed by a sum of a mean component and a fluctuating component, for example $U(t)=U+\Delta U$ and $R_s(t)=R_s+\Delta R_s$ eq. 7 will alter in the following first order ordinary differential equation (eq. 8):

$$\frac{d\Delta R_s}{dt} + \frac{\alpha R_f}{\rho c A l}\left(\frac{\pi l k_f}{\alpha R_f}(A + B\sqrt{U}) - I^2\right)\Delta R_s = \left(\frac{\pi k_f}{2\rho c A U}\right) B\sqrt{U}(R_s - R_f)\Delta U$$

The corner frequency of this equation is:

$$f_c = \frac{I^2 R_f^2 \alpha}{\rho c A l (R_s - R_f)} \approx \frac{P}{\rho c A l (T_s - T_f)} \qquad (9)$$

The latter simplification is justified because for small flows $P=I^2R_s \approx I^2R_f$. The corner frequency is dependent on the sensor temperature and thus of the applied flow. For relatively small flows the wire will not cool down significantly and there is a linear dependence between the dissipated power and the sensor temperature, see eq. 12.

The DC behaviour can be derived easily using eq. 7 because the derivative is zero.

$$T_s - T_f = \frac{P}{\pi l k_f (A + B\sqrt{U})} \qquad (10)$$

Even if radiative losses are neglected, the temperature is not constant over the hot wire. Because of conductive losses to the bulk the temperature is approximately at ambient level at the beginning and end of the hot wire. The temperature profile can be calculated (assuming it does not vary in time) by solving the following differential equation (see eq. 1):

$$A k_s l \frac{d^2 T_s}{dx^2} + (\alpha I^2 R_f - \pi d h l)(T_s - T_f) + I^2 R_f = 0 \qquad (11)$$

To make a constant temperature approximation possible, the aspect ratio must be very high. This is possible by using micro machined hot films. Therefore for a high aspect ratio eq. 11 becomes:

$$T_s - T_f = \frac{I^2 R_s}{\pi d h l} \qquad (12)$$

The corner frequency (see eq. 9) for relatively small flows thus becomes:

$$f_c = \frac{4h}{\rho c d} \qquad (13)$$

The corner frequency (for small flows) is linear dependent on the coefficient of convective heat transfer and inversely dependent on the density of the sensor material, the specific heat and the diameter (i.e. the volume) and not of the dissipated power and temperature.

Now the model of a MFS is observed. The heater is in fact a hot wire and all relations mentioned before can be applied to the heater. The temperature of the heater, T_h, is equivalent with T_s.

If the influence of the temperature sensors is neglected the model of the mass flow sensor can be derived by calculating the temperature at a certain place symmetrical around the hot wire.

Lammerink et al. [2] presented a static behaviour of the MFS based on a lumped element analysis. The temperature distribution as a function of the flow is given by:

$$T_u - T_s = (T_h - T_s)e^{\frac{1}{2a_d}\{U+\sqrt{U^2+4ga^2}\}DX}$$
$$T_d = (T_h - T_s)e^{\frac{1}{2a_d}\{U-\sqrt{U^2+4ga^2}\}DX} \qquad (14)$$
$$DT = T_d - T_u$$

Using g^{-1} as an arbitrary surface and ΔX as the spacing between the heater and sensors. The two sensors are labelled by a *u* (upstream) and *d* (downstream).

To give an impression, the temperature distribution for no-flow (solid line) and for a certain flow (dotted line) is shown in Fig. 2. The location of both sensors and heater is shown by the letters S and H, the heater has a certain width.

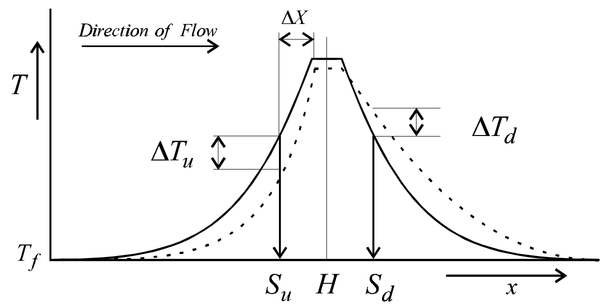

Fig. 2: Temperature distribution of a mass flow sensor.

As can be seen, the heater temperature is much higher as the sensor temperature and the sensitivity is dependant on the no-flow sensor temperature.

It's possible to implement the MFS as a three beam configuration, one heater and two sensors like Lammerink et al., see Fig. 3A, or as a two beam configuration, the heater is distributed and placed on the same carrier as the sensors. This has been done by Johnson et al. [6], see Fig. 3B.

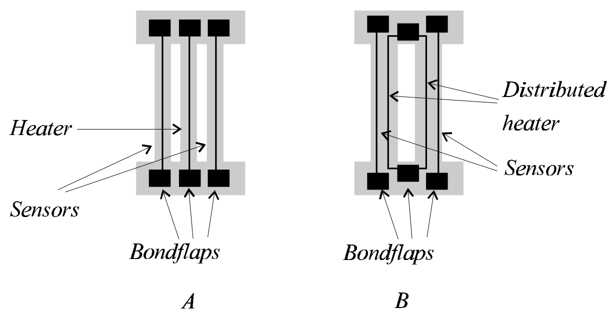

Fig. 3: Two implementations of mass flow sensors

In the two beam configuration the no-flow sensor temperature is higher than the no-flow sensor temperature of the three beam configuration resulting in a higher sensitivity. The carrier for the sensor and heater however has to be larger in order to support two wires, which results in a lower corner frequency, see eq. (13).

The temperature sensor is normally implemented as a resistor of the same material and having the same shape as the heater. Including eq. 6 the differential temperature (*DT*) is measured as:

$$\frac{DR}{R} = \frac{R_d - R_u}{R} = aDT(T_s) \qquad (15)$$

With ΔR/R the relative differential resistor value which is normally measured by using the Wheatstone bridge.

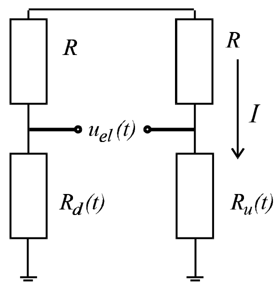

Fig. 4: Measuring a differential resistance variation.

The signal (differential output voltage due to the differential resistance variation u_{el}) equals IR·ΔR/R and the thermal noise is given by $\sqrt{4kT_sR\cdot Bw}$ (*k* is the Boltzmann's constant and *Bw* the bandwidth) and therefore the signal to noise ratio is given by:

$$\frac{S}{N} = \frac{IR\frac{DR}{R}}{\sqrt{4kT_sR\cdot Bw}} = \frac{\sqrt{P}aDT(T_s)}{\sqrt{4kT_s\cdot Bw}} \qquad (16)$$

The signal to noise ratio is proportional to the square root of the dissipated power in the sensors.

Instead of heating the sensors with a separate heater, the power of the sensors can be increased so that the sensors produce heat. This configuration is shown in Fig. 4.

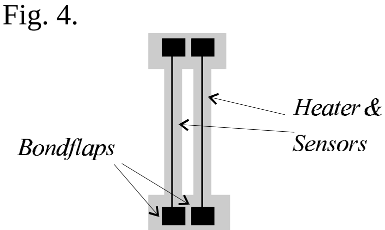

Fig. 5: The Two Sensor Microflown

The heater becomes redundant and an increase of the power in the sensors will lead to an increase of the signal to noise ratio. The carriers now have the same size as in the three beam configuration (a high corner frequency), and the no-flow sensor temperature is the same as in the two beam configuration (a high sensitivity).

When fabricated in the same technology the anemometer and the MFS heater have the same maximum allowable temperature. When exceeding this maximum temperature the wire or heater will breakdown. In the MFS, the sensors have a principally lower temperature as the heater. So when removing the heater, the power supplied to the sensors can be increased.

For all implementations of the MFS the corner frequency will be lower than the corner frequency of the hot wire anemometer. This is because the coefficient of convective heat transfer is smaller than for one sensor, since a heat source has been placed nearby and therefore heat loss decreases.

MEASUREMENTS

Two modes of the three beam MFS and the TSM have been compared in an AC flow, the result is shown in Fig 5. The three resistor values of the MFS are 300Ω and the two resistor values of the TSM are 210Ω. The configurations are compared having the temperature of the hottest element at about 500°C. The current through the sensors in the TSM is 9mA each. The current through the heater of the MFS is 11.5mA, the temperature about 500°C and the sensor currents are 3mA each.

While the signal to noise ratio increases when the sensors are fed with a larger current both heater as sensors are fed with a current of 6mA.

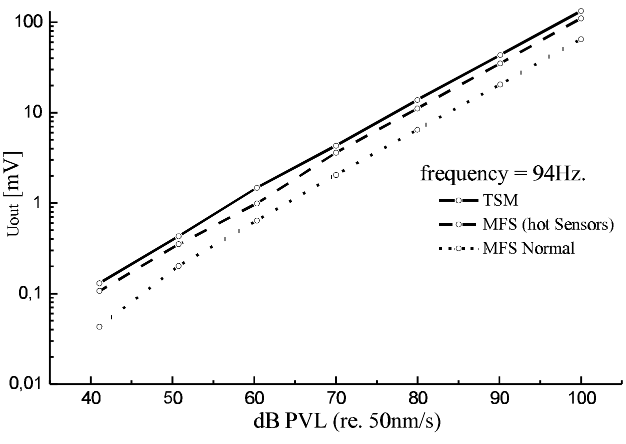

Fig. 6: Sensitivity of the TSM, the MFS with heat producing sensors and a MFS in normal operation (cold sensors).

In Fig. 7 the sensitivity of the TSM and the MFS as a function of the frequency is depicted. While the sensitivity of the MFS with hot sensors is larger only this mode is compared to the TSM. The noise level due to self noise and background noise was 30dB PVL re 50nm/s.

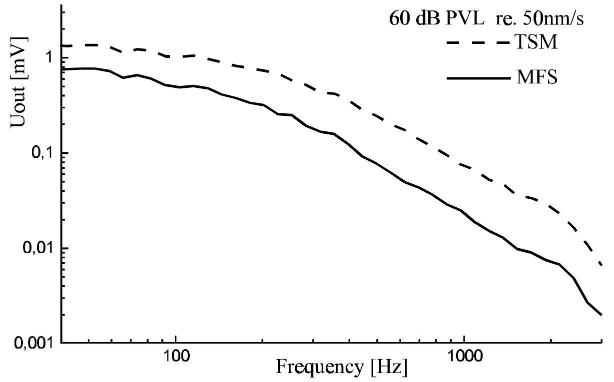

Fig. 7: Sensitivity of the TSM and the MFS with heat producing sensors as a function of the frequency.

CONCLUSION

By using qualitative models it shows that by removing the heater from a mass flow sensor the signal to noise ratio increases.

This rather surprising thought can be understood by knowing that the sensitivity of a mass flow sensor increases by increasing sensor temperature and the signal to noise ratio for measuring a resistor value is proportional with the square root of the dissipated power.

The two sensor microflown (TSM) can be seen as a mixture of an anemometer because it consists of two heated elements which are used as both sensor and heater (like the anemometer) and uses the differential temperature as a representation of the flow (like the MFS).

Measurements are performed for acoustic flows and show that the TSM performs better than a MFS. The anemometer is not able to distinguish the direction of the flow and therefore not suitable for measuring acoustic flows.

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