

A New Class of Thermal Flow Sensors Using $\Delta T=0$ as a Control Signal

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ABSTRACT

In this paper we propose a new anemometer principle. Next to the known Constant Power Anemometry (CPA) and the Constant Temperature Anemometry (CTA), here the Temperature Balanced Anemometry (TBA) is presented. A compact overview of thermal flow sensor system concepts is given. The new concept has important consequences on simple flow sensor calibration. The proposed concept is investigated using experiments on conventional thermal flow sensors. A micro flow sensor is presented in combination with an example of simple electronic interfacing circuitry.

Keywords: Anemometry, thermal flow sensor.

1. INTRODUCTION

Currently flow sensors based on thermal principles are widely used. With a thermal flow sensor the thermal energy transport (heat) which is coupled to mass transport is exploited. In one way or another heat is generated in a structure and the resulting fluid flow dependent temperature distribution is monitored. In that way the sensor system structure is that of a classical stimulus-response measurement system (see figure 1).

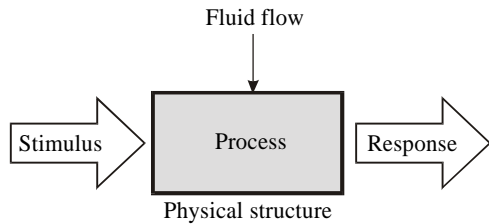


Figure 1. General structure of a thermal flow sensor. The fluid flow modulates a process, which is monitored by a stimulus-response measurement.

The stimulus is a form of heat generation and an energy transport, resulting in a response signal ΔT . The temperature measurement with a temperature sensor is absolute. This means that to measure a response signal ΔT , we need two temperature sensor signals. Here lies a source for many systematic errors in thermal flow sensor systems. Thermal flow sensors can be divided in different classes, based on [1]:

1. The driving mode, constant power or constant temperature
2. Single probe, directional insensitive, or multi-probe, directional sensitive.

The advantage of constant power driving mode is its simple electronic implementation. This mode is often referred to as Constant Power Anemometry or CPA. The disadvantage is that the temperature dependence of the fluid properties and the sensor sensitivity have to be taken into account. This can be overcome by the constant temperature driving mode, where the power needed to keep a heater at constant temperature is a measure for the flow velocity [1]. The latter method is often referred to as Constant Temperature Anemometry or CTA.

There is a wide variety of sensor versions with different ways of generating stimuli and ways of measuring response. In this paper we report on controlling a true temperature balance between the temperature sensors within the sensor structure. We refer to this thermal sensor concept as Temperature Balance Anemometry or TBA.

In the next section we will describe the TBA method and relate it to the existing methods.

2 SYSTEM MODELING

2.1 Constant Power Anemometry (CPA)

- CPA single probe

A schematic diagram of the constant power anemometer is given in figure 2. Within the physical structure a fixed amount of heat is dissipated in a resistor in the flow and the resulting temperature of that resistor is a measure for that flow. With increasing flow velocity the temperature of the sensor decreases (see figure 3a). The temperature of the sensor with respect to the ambient can be written as (King's law [2])

$$T_1 = \frac{P_1}{G_0 + K_0 \cdot v^{0.5}} + T_a \quad (1)$$

where T_a is the ambient temperature, G_0 the zero flow conductance and K_0 the flow sensitivity. So T_1 is a function of three parameters $T_1 = T_1(P_1, v, T_a)$.

If we want to 'measure' the unknown flow velocity v with a power P_1 we need to measure both T_1 as well as the ambient temperature T_a . (see figure 2). Therefore we need two temperature sensors. From the signal difference $U_1 - U_2$ and the known input power P_1 we can derive the sensor systems output signal v^* (the 'measured' flow velocity) using the flow sensor model M_{CP} . $M_1(T_1)$ and $M_2(T_a)$ are the (large signal) temperature sensor transfer functions. An example sensor model M_{CP} is given in figure 3a.

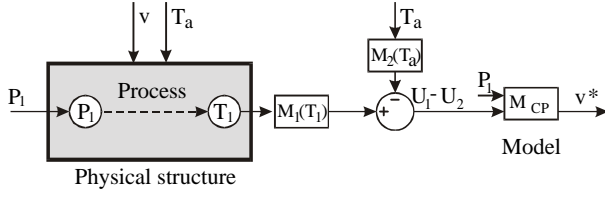


Figure 2. System structure of 'Constant Power Anemometry' (CPA) thermal flow sensor with single probe.

In a small signal analysis we can derive for dv^*

$$dv^* = m_{CP} d(U_1 - U_2) \quad (2)$$

or with the sensor sensitivities $m_1(T_1) = dU_1/dT_1$ and $m_2(T_a) = dU_2/dT_a$

$$dv^* = m_{CP} (m_1 dT_1 - m_2 dT_a) \quad (3)$$

The physical structure is designed to have an interaction between T_1 and v , but according eqn. (1) and $dP_1 = 0$ we have to write $dT_1 = s_{1v} dv + dT_a$. Doing this we find

$$dv^* = m_{CP} m_1 \left(s_{1v} dv + \left(1 - \frac{m_2}{m_1} \right) dT_a \right) \quad (4)$$

Here we see that dv^* also is a function of dT_a unless the sensor sensitivities $m_1 = m_1(T_1)$ and $m_2 = m_2(T_a)$ are equal for all temperatures involved. Because $T_1 > T_a$ it is not possible to obtain $m_1(T_1) = m_2(T_a)$ if the temperature sensor transfer functions are non-linear.

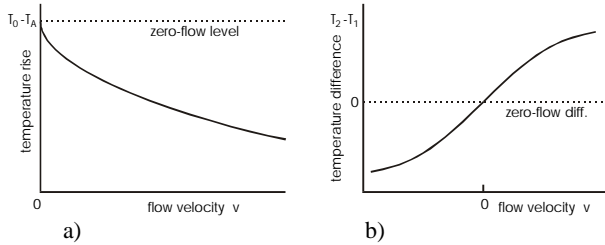


Figure 3. a) CPA single probe; temperature elevation of the temperature sensor as a function of the flow velocity. b) CPA multi-probe; typical temperature difference between two temperature sensors as a function of the flow velocity (see figure 4).

- CPA multi-probe

A way to omit a direct measurement of the ambient temperature is to implement a differential temperature measurement [3-6] (see figure 4). Furtheron, the sensor is made directional sensitive now. A typical sensor behavior given in figure 3b. For dv^* we find

$$dv^* = m_{DT} d(U_2 - U_1) \quad (5)$$

With $dT_1 = s_{1v} dv + dT_a$ and $dT_2 = s_{2v} dv + dT_a$ we find

$$dv^* = m_{DT} \left((m_2 s_{2v} - m_1 s_{1v}) dv + m_2 \left(1 - \frac{m_1}{m_2} \right) dT_a \right) \quad (6)$$

It follows that although T_a is no longer used as a reference its influence on v^* is not eliminated if $m_1(T_1) \neq m_2(T_2)$ with $T_1 \neq T_2$.

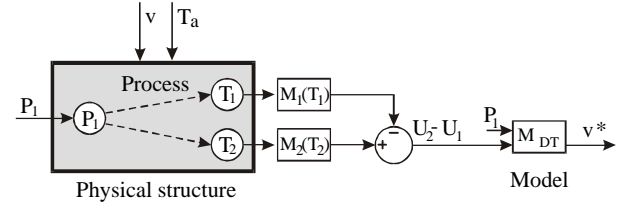


Figure 4. System structure of 'Constant Power Anemometry' (CPA) differential temperature measurement thermal flow sensor.

2.2 Constant Temperature Anemometry (CTA)

- CTA single probe

With constant temperature anemometry the absolute temperature of the temperature sensor in the physical structure (T_1 , see figure 5) is kept at a constant value above ambient (T_a). Therefore this type of flow sensor always needs a control loop [7]. The process in the physical structure described by eqn. (1) can be rewritten into

$$P_1 = (G_0 + K_0 \cdot v^{0.5}) \cdot (T_1 - T_a) \quad (7)$$

with $P_1 = P_1(v, T_1 - T_a)$. Therefore the flow velocity v can in principle be calculated from the power required to keep the temperature T_1 at a constant value above ambient. A typical sensor model M_{CT} is given in figure 6a. One advantage of this concept is the increase of the effective bandwidth of the sensor system. [7]. For a small signal analysis we first look at the open loop structure of the CTA system (see cut in figure 5). We then can calculate dP_1^* according

$$dP_1^* = b d(U_1 - U_2) \quad (8)$$

or with the known sensor sensitivities $m_1 = dU_1/dT_1$ and $m_2 = dU_2/dT_a$:

$$dP_1^* = b m_1 dT_1 - b m_2 dT_a \quad (9)$$

Now the input power P_1 is no longer kept constant (see eqn.(7)), so we have to write $dT_1 = s_{11} dP_1 + s_{1v} dv + dT_a$, and we find

$$dP_1^* = b \cdot (m_1 (s_{11} dP_1 + s_{1v} dv + dT_a) - m_2 dT_a) \quad (10)$$

in the case the loop is closed, we have $dP_1^* = dP_1$ so eqn. (10) turns into

$$dP_1^* = \frac{b m_1 s_{1v} dv + b m_1 \left(1 - \frac{m_2}{m_1} \right) dT_a}{1 - b m_1 s_{11}} \quad (11)$$

If the 'open loop gain' $b m_1 s_{11} \gg 1$, eqn. (11) reduces to

$$dP_1^* = - \left(\frac{s_{1v}}{s_{11}} dv + \left(\frac{1 - m_2/m_1}{s_{11}} \right) dT_a \right) \quad (12)$$

The flow velocity v^* is calculated from the dP_1^* signal and U_{Offset} , so we find

$$dv^* = -m_{CT} \left(\frac{s_{1v}}{s_{11}} dv + \left(\frac{1 - m_2/m_1}{s_{11}} \right) dT_a \right) \quad (13)$$

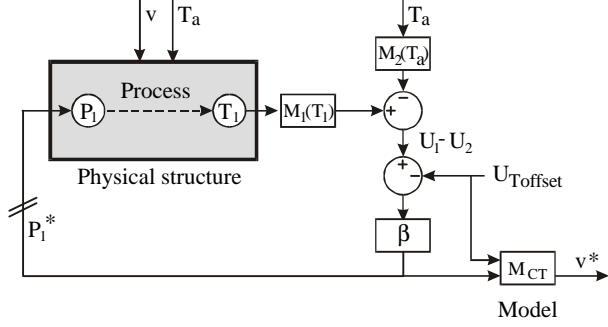


Figure 5. System structure of a 'Constant Temperature Anemometry' (CTA) thermal flow sensor. U_{Offset} is used to create a difference $\Delta(T_1 - T_a)$.

Again we see that dv^* also is a function of dT_a unless the sensor sensitivities $m_1(T_1)$ and $m_2(T_a)$ are equal. This results in a constraint for the temperature sensor sensitivities

$$m_1(T_1) = m_2(T_a), \text{ while } T_1 > T_a \quad (14)$$

If the flow sensor system is designed that way we now find for the output

$$\frac{dv^*}{dv} = m_{CT} \frac{s_{1v}}{s_{11}} \quad (15)$$

The system output v^* does not depend on the sensor sensitivity m_1 anymore.

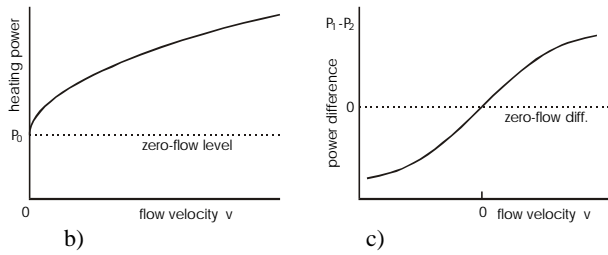


Figure 6. a) CTA single probe; heating power as a function of the flow velocity. b) CTA multiprobe; the differential heating power as a function of the flow velocity [8] (see figure 7).

- CTA multiprobe

The CTA concept can also be exploited in combination with a differential temperature measurement or differential power measurement [8] (see figure 7). An example sensor model M_{DP} is given in figure 6b. The temperature T_c of a reference probe in the flow sensor is kept constant. Without going into details we state that the system transfer function is given by

$$dv^* = m_{DP} m_2 \left(\frac{s_{21} + s_{22}}{s_{c1} + s_{c2}} \right) - s_{cv} dv - \left(1 - \frac{m_3}{m_c} \right) dT_a + m_{DP} ((m_2 s_{2v} - m_1 s_{1v}) dv + (m_2 - m_1) dT_a) + m_{DP} m_1 \left(\frac{s_{11} + s_{12}}{s_{c1} + s_{c2}} \right) s_{cv} dv + \left(1 - \frac{m_3}{m_c} \right) dT_a \quad (16)$$

To eliminate the influence of an ambient temperature change dT_a , we have the next constraints for the temperature sensor sensitivities

$$\begin{aligned} m_1(T_1) &= m_2(T_2), \quad T_1 \neq T_2 \\ m_c(T_c) &= m_3(T_a), \quad T_c > T_a \end{aligned} \quad (17)$$

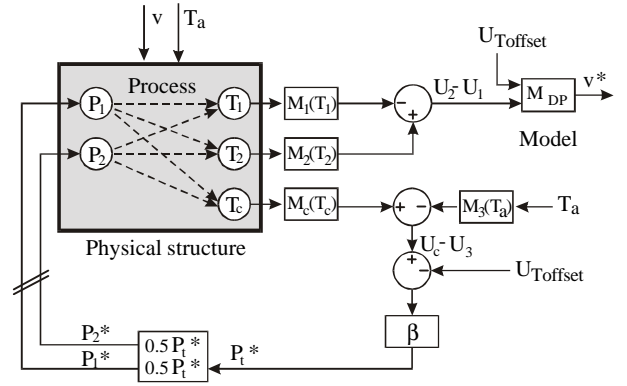


Figure 7. System structure of 'Constant Temperature Anemometry' (CTA) differential temperature measurement (differential power) thermal flow sensor [8]. The model M_{DP} function is comparable to the M_{DT} function given in figure 3c and generates the flow velocity v^* as a function of the signals $U_2 - U_1$ and U_{Offset} (used to create a difference $\Delta(T_c - T_a)$). $M_1(T_1)$, $M_2(T_2)$, $M_3(T_c)$ and $M_c(T_c)$ are large signal temperature sensor transfer functions.

2.3 Temperature Balance Anemometry (TBA)

- TBA multiprobe

In this concept, the temperature *difference* between an up-stream and a down-stream temperature sensor is kept constant at zero, by controlled distribution of a constant total heating power between an up-stream and a down-stream heater. The ratio between the up-stream and down-stream heating power is a measure for the fluid flow. The absolute temperature will not be constant: at constant total power, the average temperature of the up- and downstream sensors will decrease with increasing flow velocity. Nevertheless, this concept allows non-linear temperature sensor transfer function as long as it is symmetrical for the up- and downstream sensors. Basically, as it is truly a balance measurement, the temperature sensor pair should only indicate if the temperature difference is smaller, equal or larger than zero. Figure 8a shows the measurement system structure. The flow sensor consists of two heater-sensor pairs located in or around the flow tube, one up-stream and one down-stream. We now assume that the heater-sensor pair are located at the same position along the

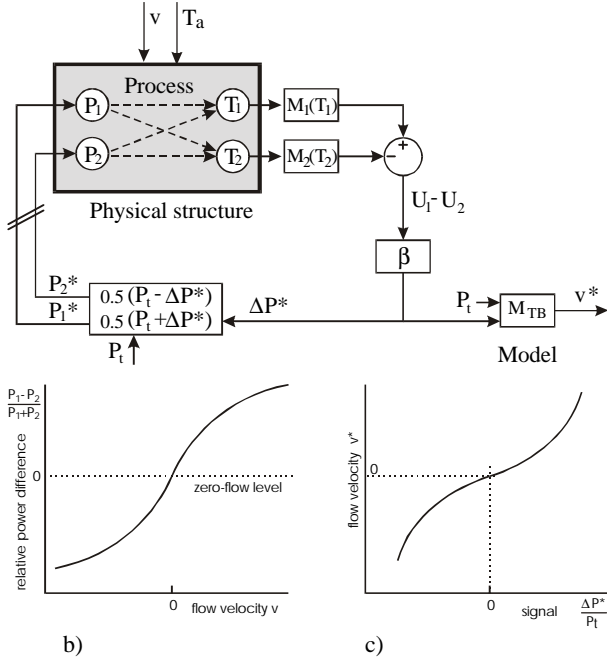


Figure 8. a) System structure of 'Temperature Balance Anemometry' (TBA) thermal flow sensor. b) The relative power difference (at $T_1=T_2$) as a function of the flow velocity. c) The model (M_{TB}) with the calculated flow velocity v^* as a function from the measured power signal ΔP^* and P_t .

length of the tube. In general this is not necessary. The two heaters are driven by power P_1 and P_2 respectively. Their temperatures T_1 resp. T_2 , are determined by the heat transport in the flow sensor, which is modulated by the flow velocity. The temperatures T_1 and T_2 are measured and their difference is taken as the signal containing the information about the flow velocity. For a small signal analysis we look at the open loop structure (see cut in figure 8a). We now calculate $d\Delta P^*$

$$d\Delta P^* = b d(U_1 - U_2) \quad (18)$$

or with the known sensor sensitivities $m_1=dU_1/dT_1$ and $m_2=dU_2/dT_2$

$$d\Delta P^* = b m_1 dT_1 - b m_2 dT_2 \quad (19)$$

rewriting the temperature variations dT_1 and dT_2 and writing dP_1 and dP_2 in terms of $d\Delta P^*$ (closed loop and assuming $dP_t=0$) results in

$$\begin{aligned} dT_1 &= s_{11}dP_1 + s_{12}dP_2 + s_{1v}dv + dT_a \\ dT_2 &= s_{21}dP_1 + s_{22}dP_2 + s_{2v}dv + dT_a \\ dP_1 &= 0.5(dP_t + d\Delta P^*) \Rightarrow dP_1 = 0.5d\Delta P^* \\ dP_2 &= 0.5(dP_t - d\Delta P^*) \Rightarrow dP_2 = -0.5d\Delta P^* \end{aligned} \quad (20)$$

eqn. (20) into eqn. (19) results in

$$d\Delta P^* = \frac{bm_1(s_{1v}dv + dT_a) - bm_2(s_{2v}dv + dT_a)}{1 - 0.5b(m_1(s_{12} - s_{11}) + m_2(s_{21} - s_{22}))} \quad (21)$$

If the 'open loop gain' $0.5b(m_1(s_{12} - s_{11}) + m_2(s_{21} - s_{22})) \gg 1$, and again the next constraint for the temperature sensor sensitivities is fulfilled

$$m_1(T_1) = m_2(T_2), \text{ while } T_1 = T_2 \quad (22)$$

eqn. (21) reduces to the next equation for dv^*

$$\frac{dv^*}{dv} = m_{TB} \frac{2(s_{1v} - s_{2v})}{s_{11} - s_{12} + s_{22} - s_{21}} \quad (23)$$

The system output v^* does not depend on the sensor sensitivities $m_1(T_1=T_2) = m_2(T_2=T_1)$, anymore. The constraint that there should be equal temperature sensor sensitivities (eqn. (22)) now is less severe than earlier one (eqn.(14)), because the absolute temperatures are equal now; $T_1 = T_2$, so the temperature sensors may be *non-linear* and still fulfill the demands to eliminate the dT_a sensitivity and to cancel the temperature sensor sensitivity from the transfer function. This is the significant advantage for the proposed TBA concept.

3. THERMAL MODEL

A typical example of a physical structure used in conventional mass flow sensors is a capillary tube with two or more heater-sensor elements. A schematic view of such a structure is given in figure 9 (see also figure 14).

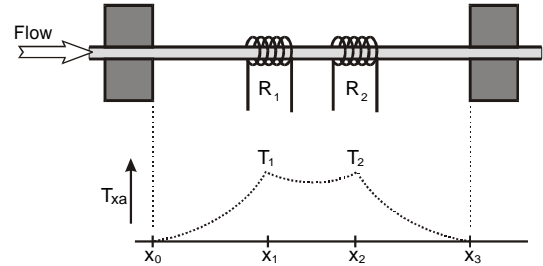


Figure 9. Stainless steel tube with two resistors which act as a heater as well as a temperature sensor. Two thermally highly conductive blocks define the temperature at the tube ends at ambient level.

The two resistor elements R_1 and R_2 are simultaneously used as actuator as well as temperature sensor. At both ends the tube is fixed in thermal highly conductive blocks which are at ambient temperature. In a simplified thermal model the tube is considered to be one-dimensional with a uniform temperature in the radial direction. We assume an effective conductivity in the x direction equal to $A_w k_w + A_f k_f$ with A_w, A_f the surface areas of the wall and the fluid and k_w, k_f the thermal conductivities of the wall and the fluid. The heat loss to the environment at T_a is modeled with a heat-transfer coefficient h . This results in the next differential equation for the temperature $T_x - T_a = T_{xa}$

$$(A_w k_w + A_f k_f) \frac{d^2 T_{xa}}{dx^2} - A_f r c v \frac{dT_{xa}}{dx} - h T_{xa} = 0 \quad (24)$$

with \mathbf{r} the fluid density, c the fluid heat capacity at constant pressure and v the flow velocity. Equation (24) is a second order linear differential equation in T_{xa} . Solving the differential equation results in the general temperature distribution function

$$T_{xa}(x) = \mathbf{a} \exp(I_1 x) + \mathbf{b} \exp(I_2 x) \quad (25a)$$

with

$$I_{1,2} = \frac{v \pm \sqrt{v^2 + 4h(A_w \mathbf{k}_w + A_f \mathbf{k}_f) / A_f^2 \mathbf{r}^2 c^2}}{2(A_w \mathbf{k}_w + A_f \mathbf{k}_f) / A_f \mathbf{r} c} \quad (25b)$$

and \mathbf{a} and \mathbf{b} depending on the boundary conditions. In order to solve the temperature distribution, the sensor structure is devised into three parts, each with its own boundary conditions. In the configuration of figure 9 with the TBA method, the boundary conditions are $T_{xa}(0)=T_{xa}(L)=0$ and $T_{xa}(x_1) = T_{xa}(x_2)$. The temperature amplitude is found from the heat balance and $P_1+P_2=P_t$. The temperature distribution for three different flow velocities is given in figure 11a. The relative power difference $(P_1-P_2)/P_t$ is given in figure 11b.

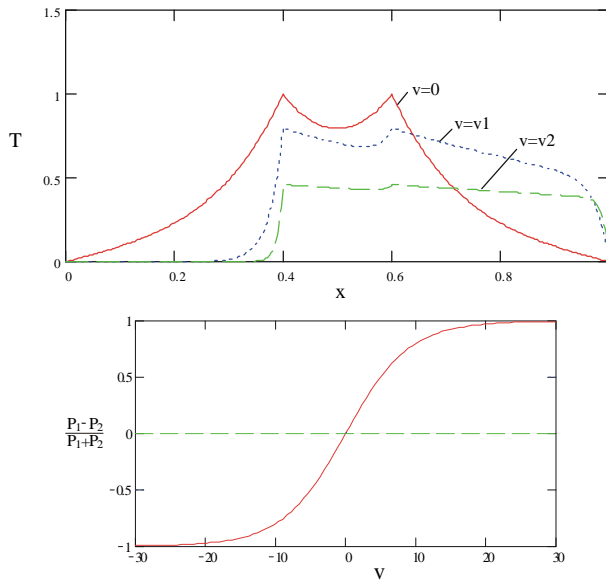


Figure 11. a) Temperature distribution of T_{xa} as a function of the relative position x on the tube for three different flows. b) The calculated relative power difference $(P_1-P_2)/P_t$ of the two heaters R_1 and R_2 as a function of the flow velocity.

4. EXPERIMENTS

First experiments on the concept are carried out on a conventional flow sensor tube consisting of a stainless steel hollow tube (0.4 x 0.7 mm ϕ) with 6 wire wound resistors around it (each 3 mm long) which can act as a sensor as well as an actuator (see figure 14). A schematic view of the measurement setup with the sensor tube is given in figure 13. The fluid flow through the tube is steered by a mass flow controller. The system controller in the setup is implemented on a personal computer using Labview. The power dissipated

in a resistor is measured by measuring the current through and the voltage over the resistor using a four point measurement method. In this way the dissipated power is known independent from the actual resistor value ($P_R(T)=I_R(T)*V_R(T)$). At the same time the temperature from the resistor is calculated from the measured actual resistor value ($R(T)=V_R(T)/I_R(T)$) and a known calibration formula for that resistor

$$R(T) = R_{Ta} (1 + \mathbf{a}(T - T_a)) \quad (26)$$

The results obtained with these experiments are given in figure 15 and are in good qualitative agreement with the theory.

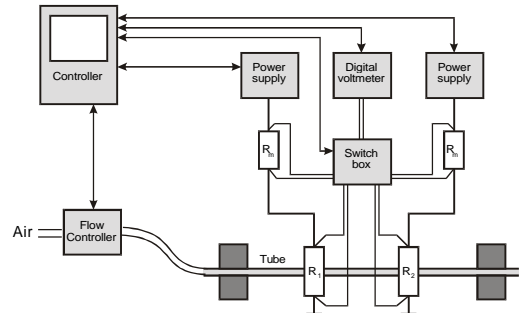


Figure 13. Measurement setup for automatic controlling the heater powers and for measuring the resistor temperatures.

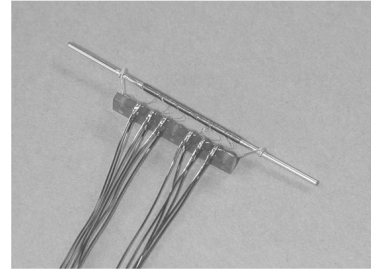


Figure 14. Photograph of the capillary tube flow sensing structure used in our experiments. The tube inner and outer diameter are 0.4 mm and 0.7 mm respectively. Six wire wound resistors (length 3 mm) can act as heater-sensor elements.

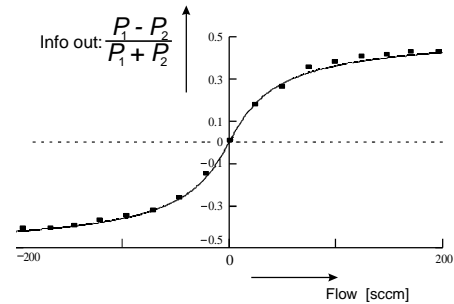


Figure 15. Output signal of the controller $(P_1-P_2)/(P_1+P_2)$ as a function of the applied flow. The square blocks are the measured points. The continuous line is the model result as shown in figure 12 and fitted with a scale factor for $(P_1-P_2)/P_t$.

In a second experiment the TBA system is implemented using a micro flow sensor as physical structure (see figure 16a and figure 17b). The electronic TBA controller was designed around a thermal oscillator (see figure 16b and figure 17a). The sensor system is tested

with a flow velocity v from -2 m/s to 2 m/s. The pulse width modulated output signal of the oscillator is linear with the flow velocity and varies in the experiment from 45% to 55%.

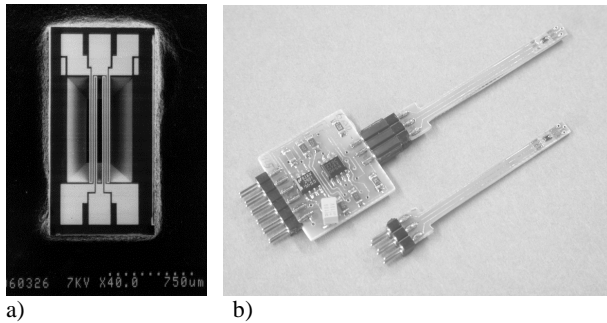


Figure 16. a) Photograph of the micro flow sensor structure with four meander shaped thin film resistors. For a cross section see figure 17b. b) Photograph of a TBA sensor system with the micro sensor on the tip of a stick and the TBA controller mounted on a 1'' x 1'' PC-board.

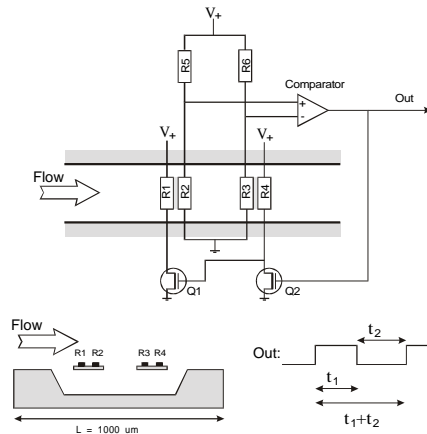


Figure 17. a) Schematic diagram of a relative simple thermal oscillator [see also 10] used as a TBA controller. The timing of the output signal $((t_1 - t_2)/(t_1 + t_2))$ directly represents the $\Delta P/P_i$ signal. b) Cross section of the micro flow sensor. The resistors are supported by $1 \mu\text{m}$ thick and $80 \mu\text{m}$ wide silicon nitride bridges at $40 \mu\text{m}$ distance from each other.

5. DISCUSSION & CONCLUSIONS

We have introduced a new flow measurement method based on a dual probe thermal flow sensor: Temperature Balance Anemometry (TBA). Four existing thermal flow sensor measurement methods have been analyzed and compared with the TBA: CPA single and dual probe, CTA single and multi-probe. In both the CTA single probe, and the TBA dual probe method, the flow measurement is based on thermal balance, and if temperature sensors symmetry is provided the temperature sensor transfer function is eliminated in the flow sensor transfer function. In the TBA method the sensor output is derived from the distribution of the heating powers between the two heater/sensor couples. This means that the sensor transfer function is completely determined by the thermal and the flow properties of the sensor. In all five of the analyzed

methods the sensitivity of the sensor output for changes of the ambient temperature can be eliminated if in the whole measurement range the temperature sensor sensitivities are equal. In all but the TBA method this implies that temperature dependent sensitivities are not allowed, which means that the transfer functions of the temperature sensors should be linear. In the TBA method temperature symmetry is maintained, which means that the temperature sensors with equal temperature dependent transfer functions are allowed, also non-linear ones. This opens the way towards the use of for example highly sensitive metal-semiconductor thermocouples, which are strongly non-linear but provide good symmetry. Two experiments have shown the feasibility of the TBA method.

6. ACKNOWLEDGEMENTS

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REFERENCES

- [1] B.W. van Oudheusden, Silicon thermal flow sensors, *Sensors and Actuators*, A30 (1992), p.5-26
- [2] L.V. King, On the convection of Heat from small Cylinders in a Stream of Fluid: Determination of the Convection Constants of Small Platinum Wires, with Applications to Hot-Wire Anemometry, *Proc. R. Soc. London*, vol. 90, 1914, p.563-570
- [3] R.G. Johnson and R.E. Higashi, A Highly sensitive silicon chip microtransducer for air flow and differential pressure sensing applications, *Sensors and Actuators*, 11 (1987), p. 63-72
- [4] R.G. Johnson and R.E. Higashi, Semiconductor device, US patent nr: 4651564
- [5] T.S.J. Lammerink, N.R. Tas, M.Elwenspoek and J.H.J. Fluitman, Micro liquid flow sensor, *Sensors and Actuators*, 37-38 (1993), p. 45-50
- [6] H.E. De Bree, H.V. Jansen, T.S.J. Lammerink, G.J.M. Krijnen and M. Elwenspoek, Bi- directional fast flow sensor with large dynamic range, *Proc. MME '98*, Ulvic (Norway) June 3-5, 1998, p. 194-197
- [7] L.M. Fingerson and P.Freymuth, Thermal Anemometers, in: *Fluid mechanics measurements*, ed. R.J. Goldstein, Taylor & Francis, Bristol (1996), pp.115-173
- [8] B.W. van Oudheusden, The thermal modeling of a flow sensor based on differential convective heat transfer, *Sensors and Actuators*, A29 (1991), p.93-106
- [9] J.H. Huijsing and F.R. Riedijk, Integrated semiconductor circuit for thermal measurements', US patent nr: 5064296
- [10] Y. Pan, F.R. Riedijk and J.H. Huijsing, A New Class of Integrated Thermal Oscillators with Duty-cycle Output for Application in Thermal Sensors, *Sensors and Actuators*, A21-A23 (1990), p. 655-659
- [11] H.J. Verhoeven, Smart Thermal Flow Sensors, PhD. Thesis, Delft University Press, Delft, The Netherlands, 1995.
- [12] G.C.M. Meyer and A.W. van Herwaarden, Editors, *Thermal Sensors*, Sensors Series with Series Editor B.E. Jones, Institute of Physics Publishing, Bristol and Philadelphia, 1994.