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EVALUATION ON THERMOCOUPLES FOR THE THERMAL TIME-OF-FLIGHT FLOW MEASUREMENT

Eberhard Engelien[1], Okan Ecin[2], Reinhard Viga[1], Bedrich Hosticka[2], Anton Grabmaier[1]

University Duisburg-Essen, Department of Electrical Engineering and Information Technology,
[1]Institut of *Elektronische Bauelemente und Schaltungen*; [2]Institut of *Mikroelektronische Systeme.*

ABSTRACT

The authors report on a flow measurement technique using the Thermal Time-of-Flight (TTOF) method. In this work the velocity of air flowing through a pipe was investigated. For this purpose a filament and several thermocouples were adopted. The filament served as a signal transmitter, which injected thermal pulses into the flowing fluid in the pipe. The generated thermal pulses propagated along the flowing direction towards the thermocouples. In three defined distances the injected thermal pulses were detected by three identical thermocouples, respectively. The time behaviour of the measured output signals was computed using the cross-correlation process. The time delay of the output signals combined with the knowledge of the distances resulted in the flow velocity. In this work, a flow measurement technique in the velocity range of v_{min} = 0.01 m/s up to v_{max} = 1.20 m/s is presented considering laminar flow.

Index Terms – thermal velocity measurement, pulsed heat injection, Time-of-Flight, thermocouples, cross-correlation.

1. INTRODUCTION

The use of mass and volume flow measurement techniques is essential in industries for process control purposes, e. g. of gases and liquids. In recent years several different types of sensors were developed [5]. Depending on the standards, for example metering precision, flow ratio, permitted decrease of pressure and also for the cost of production, different measurement principles are applied. The utilization of these measurement systems is mostly dependent on pressure, temperature, density, viscosity and homogeneity of the fluid. Hence, flow sensors must be calibrated and maintained for certain application.

Thermal flow measurement is currently based on the measurement of displacement of heat against the velocity of the fluid. The heat is induced through the passing of the fluid by a permanently heating element. This kind of sensor is only applicable for gases with known properties [2][4][8]. In contrast to, the aim of the presented investigations is to present a solution for measuring the flow of any kind of fluid with unknown properties. This solution is intended to be low-maintenance and exempt from calibration. The Thermal Time-of-Flight (TTOF) principle via the induction of mobile heat pulses in the flow of gases and liquids is key of the investigations [1].

2. MATERIALS AND METHODS

The focus of this paper deals with the gas flow measurement using the example of air. In the following are described the pilot test for sensor materials and measurement equipment, the construction of the TTOF gas flow sensor and the theory of heat transmission between the heating element and the temperature sensors. For the interpretation of the output sensor signals signal processing theory is illustrated at last.

2.1. Experimental Setup for Pilot Test

The objective of the pilot test was to determine the potential construction of a sensor as well as a measurement device. Therefore, a circular PVC-disc with heated copper sticks (Figure 1) was constructed as a pulse generator. The copper sticks were heated up to ΔT = 0.1 K - 10 K.

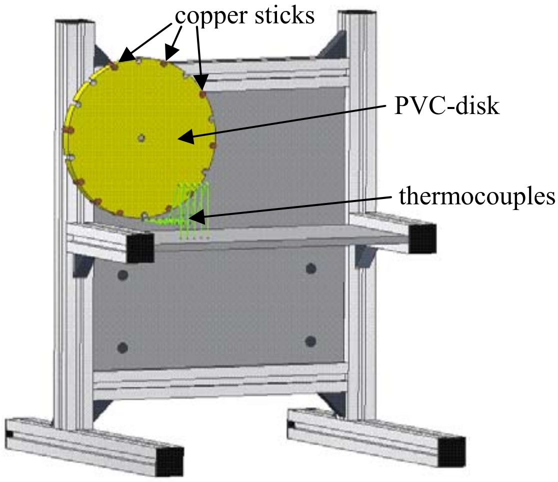

Figure 1: Rotating PVC-disc (yellow) with heated copper sticks (red) above an array of thermocouples (green).

The circular PVC-disc ($Ød_{disc}$ = 111.2 mm) rotated above an array of thermocouples (TC) type K ($Ød_{TC}$ =

0.01 mm - 0.05 mm) to determine the speed of response of the thermocouples, the detection of the minimum temperature deviation, and the sampling rate. The heat transfer between copper sticks and thermocouples was given by thermal conduction. The copper sticks exhibited a differential thermal energy of ΔE_{th} = 0.30 J (@ ΔT = 0.1 K) – 29.67 J (@ ΔT = 10 K) to the environment.

$$\Delta E_{th} = m \cdot c \cdot (T_{at+\Delta T} - T_{at}) \qquad (1)$$

m – mass [kg]
c_p – specific heat capacity [J/(kg·K)]
T_{at} – absolute ambient temperature [K]

The thermocouples required a differential thermal energy of ΔE_{th} = 1.54 nJ (@ $Ød$ = 0.01 mm) to ΔE_{th} = 0.19 µJ (@ $Ød$ = 0.05 mm) to heat up at least 0.1 K. The potential heat flow dQ_{th}/dt between the copper sticks and the thermocouples was dQ_{th}/dt = 8.20 mW. Therefore, the conditions were met to detect quickly a minimum temperature deviation.

$$\dot{Q}_{th} = \frac{\lambda}{\delta} \cdot A \cdot (\vartheta_{at+\Delta T} - \vartheta_{at}) \qquad (2)$$

λ – specific heat conductivity [W/(m·K)]
δ – heat path [m]
ϑ_{at} – ambient temperature [°C]
A – surface of the thermocouple [m^2]

2.2. Experimental Setup of a Gas Flow Sensor

For the investigation of the gas flow sensor an acryl glass pipe with a diameter of $Ød_{pipe}$ = 40 mm consisting of three parts was used: The supply pipe was l_{sup} = 1100 mm, the sensor pipe l_{sens}= 100 mm and the effuser l_{eff} = 200 mm long. A ventilator (SEPA MFB40D-12H) generated an air flow between v_{min} = 0.25 m/s and v_{max} = 1.23 m/s. Figure 2 and Figure 4 demonstrate the sensor construction. As heating element (1) a nickel-chrome filament with a width of 1 mm and a thickness of 0.2 mm was used.

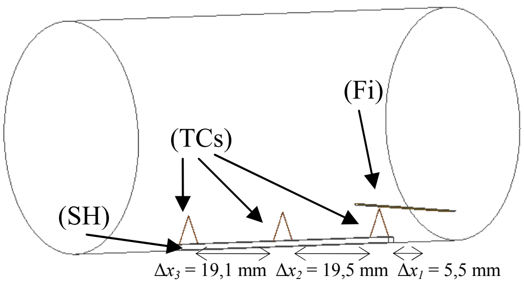

Figure 2: Gas flow sensor construction (drawing); filament (Fi), thermocouples (TCs), sensor holder (SH).

For the thermal detection one thermocouple (TC) type K ($Ød_{TC}$ = 0.08 mm) from Newport Electronics GmbH (OMEGA) was deployed to control the temperature of the filament. Another three thermo-couples (TCs) also type K ($Ød_{TC}$ = 0.05 mm) of the same batch absorbed the heat of the passing heating pulses. The origin of the thermocouples from the same batch is crucial as it ensures identical reaction and delay times. The distance between the filament and the first TC was Δx_1 = 5.5 mm, from the first TC to the second TC Δx_2 = 19.5 mm, and from the second TC to the third TC Δx_3 = 19.1 mm. The filament and the TCs were vertically plugged y = 5.9 mm into the pipe. At this level one obtains the mean velocity of the passing gas (Figure 3). The output voltage of the TCs was measured by a Spider 8 - SR01 signal acquisition system from Hottinger Baldwin Messtechnik GmbH (HBM). The results were displayed by the software Catman Professional from HBM, respectively.

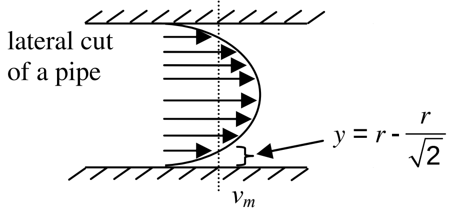

Figure 3: Parable of a laminar gas flow with mean velocity and its intersection points.

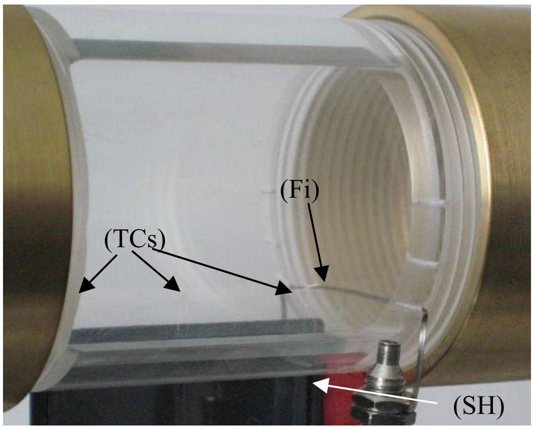

Figure 4: Gas flow sensor construction (breadboard construction); filament (Fi), thermocouples (TCs), sensor holder (SH).

For the filament the intention was to generate square heat pulses. For this purpose the filament was powered by a HAMEG 8143 power supply unit which induced a periodic steplike voltage signals (8 V for 25 ms, 6 V for 75 ms, 5 V for 100 ms, 0 V for 2 s). Due to the thermal dissipation loss inside the filament heat pulses were generated on the filament surface. Convection was the predominant reason for the heat transfer from the filament surface to the air [9].

$$Q_{th} = \alpha \cdot A \cdot \Delta\vartheta \cdot \Delta t \qquad (3)$$

$$\alpha = \frac{\lambda}{L} \cdot Nu \qquad (4)$$

$$Nu = 0.0664 \cdot (\mathrm{Pr})^{1/3} \cdot (\mathrm{Re})^{1/2} \qquad (5)$$

Q_{th} – heat convection energy [Ws]

α – heat transfer coefficient [W/(m²·K)]
A – heating surface [m²]
$\Delta\vartheta$ – temperature difference [K]
Δt – time difference to traverse the contemplated surface (dependent on velocity) [s]
L – width of the filament [m]
Pr – Prandtl number
Re – Reynolds number
Nu – Nusselt number

$$\mathrm{Pr} = \frac{\eta}{a \cdot \rho} \quad (6)$$

$$\mathrm{Re} = \frac{v_m \cdot L \cdot \rho}{\eta} \quad (7)$$

η – dynamic viscosity [kg/(m·s)]
a – thermal diffusivity ($\lambda/(c_p \cdot \rho)$) [m²/s]
ρ – density [kg/m³]
v_m – mean velocity [m/s]

In the following the theoretic behaviour of a defined volume of air passing by the filament and the three thermocouples will be described.

A volume of V = 4 mm³ of air passes the filament symmetrically (as shown in Figure 5) in a time Δt (dependent on velocity) and with an existing temperature difference of ΔT = 10 K. Table 1 shows the potential heat convection and the differential thermal energy $\Delta E_{th,air}$ of the air at the thermocouples.

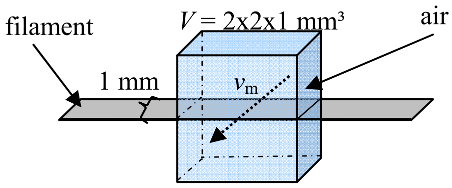

Figure 5: A cube of 4 mm³ of air passing the filament.

Regarding the gas flow it is significant to consider that there is forced convection in the direction of flow and natural convection at the level of the pipe cross section. The proportion of natural to forced convection is 1:10 till 1:100 (dependent on velocity) [9].

Table 1: Potential differential thermal energy at the thermocouples in addition to the velocity by $\Delta\theta$ = 10 K.

v_m [m/s]	$\Delta E_{TC\,air}$ [J]	ΔE_{TC1} [J]	ΔE_{TC3} [J]	ΔE_{TC3} [J]
0.1	1.122	0.776	0.408	0.254
0.2	0.793	0.487	0.229	0.136
0.4	0.561	0.297	0.125	0.072
0.6	0.458	0.219	0.087	0.049
0.8	0.397	0.175	0.067	0.037
1.0	0.355	0.147	0.054	0.030
1.2	0.324	0.127	0.046	0.025
1.4	0.300	0.112	0.040	0.022

Table 1 presents that the air heated by the filament contains enough thermal energy to heat up the thermocouples which need ΔE_{th} = 0.19 µJ (Ød = 0.05 mm) by a given distance of nearly Δx = 50 mm and a velocity of more than v_m = 1.4 m/s.

2.3. Signal Processing

For measuring the velocity in a flowing fluid through a pipe signal processing methods were used. A simple model of a transfer channel was applied in this work. The fluid in a pipe itself represented the transfer channel. A heated filament positioned in the pipe acted as a thermal signal transmitter. At a proper distance thermocouples were arranged for the detection of the thermal pulses. The generated thermal pulse propagated along the fluid and reached the detection points. The time a thermal pulse required for the defined distance gave information about the fluid velocity. This measurement principle is known as the Thermal Time of Flight (TTOF) method.

The filament was biased with a periodically time dependent voltage signal generating the thermal pulses in the fluid. The pulses were transmitted through the fluid reaching three thermocouples at three distinguished positions. Hence, the output signals of these thermocouples showed dependence in amplitude and time behaviour. Since the output signals of the thermocouples were compared with regard to their time behaviour, the cross-correlation technique was applied. Correlating the first output signal $x_{T1}(t)$ with both, the second $x_{T2}(t)$ and the third $x_{T3}(t)$ signal, two cross-correlation functions $R_{xT1xT2}(\tau)$ and $R_{xT1xT3}(\tau)$ were obtained as a function of the time delay τ between these signals. The mathematical expression of the cross-correlation is given for two different signals $x(t)$ and $y(t)$ as:

$$R_{xy}(\tau) = \frac{1}{T}\int_0^T x(t+\tau) \cdot y^*(t)\,dt \quad (8),$$

where T denotes the time length of the signal and $y^*(t)$ the conjugate-complex value of the signal $y(t)$.
For time-discrete sampling values N the cross-correlation function yields:

$$R_{xy}(k) = \frac{1}{N-|k|}\sum_{n=0}^{N-1} x(n+k) \cdot y(n) \quad (9),$$

with k as the dependent sampling value.
For an improved evaluation the normalized cross-correlation was computed. The normalized cross-correlation is noted as the cross-correlation coefficient $R_{xy,norm}(\tau)$ [7]:

$$R_{xy,norm} = \frac{R_{xy}(k)}{\sqrt{R_{xx}(0) \cdot R_{yy}(0)}} \quad (10).$$

Obtaining the cross-correlation coefficients of the three output signals of the thermocouples the time delay between these signals was determined.

3. RESULTS

The main target of the described investigations consisted in characterising and testing the flow of heat pulses in a moving fluid using the example of air. The results of the measurements rely on the capture of the temperature by the thermocouples.

3.1. Pilot Tests

The investigations with simulated mobile heat pulses inducted through copper sticks showed that thermocouples (TC) with minor diameter as receiving devices were able to detect heat pulses with a temperature difference of ΔT = 0.1 K to ambient temperature. The heat transfer results from heat conduction. In addition, a sampling rate of up to f_r = 10 kHz with qualified thermal signals was achieved. Therefore the conditions for the engineering of a flow sensor were met.

3.2. Gas Flow Sensor

The arrangement of filament and the thermocouples (Figure 4) offered the possibilities for the development of a TTOF gas flow sensor. In Figure 6 is presented an example for the distribution of heat at a differential air volume behind the filament. The mean velocity was v_m = 0.1 m/s.

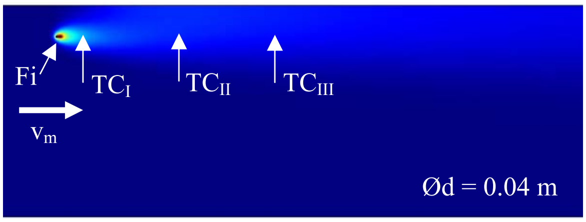

Figure 6: Computed distribution of heat after the filament at a mean velocity of 0.1 m/s; filament (Fi), location of the thermocouples (TC_I – TC_{III}).

The heat transfer occurs in a band width of $\Delta y \approx 5$ mm - 6 mm and a length of nearly $\Delta x \approx 80$ mm. The temperature difference falls at the first 10 mm rapidly. Afterwards a slower decay is observed.

Table 2: Measured temperature differences of the four thermocouples at different mean velocities.

v_m [m/s]	ΔT_{TC0} [T]	ΔT_{TC1} [T]	ΔT_{TC2} [T]	ΔT_{TC3} [T]
0.32	4.1	2	1.4	1.1
0.43	3.5	1.5	1.2	1.0
0.57	3.0	1.3	1.1	0.9
0.70	2.6	1.1	0.9	0.8
0.82	2.2	1.0	0.8	0.7
0.95	2.0	1.0	0.8	0.6
1.08	1.8	1.0	0.7	0.5
1.20	1.7	0.8	0.6	0.3

Table 2 renders the temperature difference of the temperature at the TCs due to the passing heat pulse and the general temperature of the medium. These values are presented for different mean velocities. Thereby is indicated that only for slow velocities a major temperature difference (more than 2 K) exists at TC0 and TC1. Accordingly, the decline of temperature differences between the TCs is much smaller for TCs further away from the filament or when the velocity increases, as shown in Figure 6.

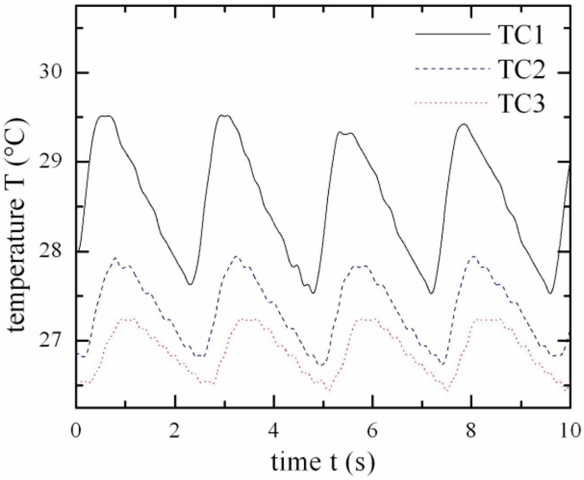

Figure 7: Measured heat pulses at the thermocouples TC1- TC3 at a velocity of v_m =0.1 m/s.

Figure 7 depicts the output signals of the three thermocouples TC1, TC2 and TC3 in a time segment of 10 seconds. The input signal is a periodic signal with a fast rise time generating a steep temperature increase. The decay time of the output corresponds to the response time of the thermocouples. The thermal heat pulse generated by the filament strikes first TC1. After the distance Δx_2 between TC1 and TC2 the pulse reaches TC2. Finally passing distance Δx_3 TC3 detects the thermal signal. A time delay at the output signals is observed.

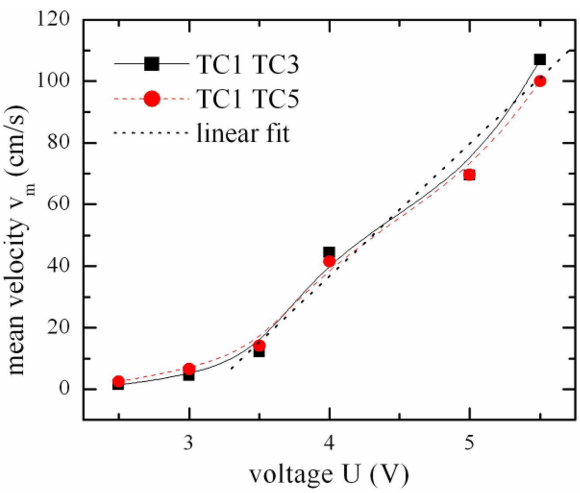

Figure 8: Measured mean velocity to the output voltage applied at the ventilator.

The mean velocity of the flowing air is obtained by cross-correlating the output signals both TC1 with TC2 and TC1 with TC3. In Figure 8 the mean velocity v_m is displayed as a function of the applied voltage U to the ventilator. With the use of equation (8) the time delay between the signals is calculated leading to the mean flow velocity. At a velocity range of v_m = 0.05 m/s a slight dependence of the applied voltage is noticeable. Beyond a velocity of v_m = 0.1 m/s a well-defined linear behaviour is shown up to a velocity of v_m = 1.0 m/s.

4. DISCUSSION

The above results demonstrate that the TTOF principle is applicable to a gas flow measurement, as the movement of the heat pulse could be detected by the experimental setup for high velocities and large distances.

The measurements listed in Table 2 correspond to the expected results in Table 1 and support therefore the previous calculations and the compiled models.

The temperature differences shown in Table 2 correspond to the thermal energy distribution. The temperature course in dependence of the velocity and the distance to the filament in direction of flow can be approximated by the function $f(x) = b/(x+1/\Delta T \cdot b)$. Thereby the temperature difference is ΔT = 10 K and the parameter b decreases as the velocity increases.

For further investigations the results give indication how to position the elements for temperature detection. Furthermore, it will be possible to define larger distances because higher velocities and therefore lower temperature margins can also be detected in larger distances from the pulse source. Larger distances are key for a more accurate velocity measurement.

A challenge that became obvious during the temperature measurements is to obtain a high noiseless sampling rate due to the small and weak nature of the temperature signals (for the velocity of v_m = 1 m/s and a distance of $\Delta x \approx 0.02$ m between the thermocouples a sampling rate of minimum 500 Hz is required).

The output signals of the different positioned thermocouples show an expressive similarity in their signal form. The amplitude decreases with the increasing distance of detection. More significant is the time shift of the output signals. This is crucial for the determination of the flow velocity. Since a time shift is observed in the output signals, the time delay can be calculated by cross-correlation. This in turn denotes the time a heat pulse needs to travel a certain distance. With the corresponding distance the flow velocity is obtained. In Figure 8 it is shown, that both cross-correlations T1 with T2 and T1 with T3 are in good agreement and result in the same velocities.

5. SUMMARY

In conclusion, a Thermal Time-of-Flight model has been demonstrated for the determination of flow velocity. Using heat as the transferring parameter is quite appropriate for Time-of-Flight measurements, since heat is applicable for transport phenomena in a wide spectrum of fluids. Furthermore, heat is an excellent carrier in any fluid and can be transferred in an extremely good way by heat conduction. The adopted thermocouples in this work are suitable for the velocity range operated in these measurements. These show a proper response characteristics and a sufficient fast decay time. Heat pulses propagating through a fluid are required for determining the time delay between the output signals. Hence, cross-correlation is the most suitable application method in the signal processing domain.

In perspective, different fluids - liquids and gases, are going to be investigated with this kind of measurement technique. Also gas mixture can be considered as inspecting medium. Referring to the input signal forms the so-called Pseudorandom Noise sequences (PN-sequences) can be taken into account for generating thermal pulses. These kinds of signal forms promise a more clearly cross-correlation peak, which is more adequate by higher flow velocities and even in the turbulent flow range of any fluid.

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