Information Technology and Electrical Engineering - Devices and Systems, Materials and Technologies for the Future

Faculty of Electrical Engineering and Information Technology

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http://www.db-thueringen.de/servlets/DocumentServlet?id=14089
EVALUATION ON THERMOCOUPLES FOR THE THERMAL TIME-OF-FLIGHT FLOW MEASUREMENT

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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 \( v_{\text{min}} = 0.01 \text{ m/s} \) up to \( v_{\text{max}} = 1.20 \text{ m/s} \) 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 \( \Delta T = 0.1 \text{ K} - 10 \text{ K} \).

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

The circular PVC-disc (\( \Omega d_{\text{disc}} = 111.2 \text{ mm} \)) rotated above an array of thermocouples (TC) type K (\( \Omega d_{\text{TC}} = \))
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 \( \Delta E_{th} = 0.30 \text{ J} \) (\( @ \Delta T = 0.1 \text{ K} \)) – 29.67 J (\( @ \Delta T = 10 \text{ K} \)) to the environment.

\[
\Delta E_{th} = m \cdot c_p \cdot (T_{at+\Delta T} - T_{at}) \quad (1)
\]

\( m \) – mass [kg]

\( c_p \) – specific heat capacity [J/(kg·K)]

\( T_{at} \) – absolute ambient temperature [K]

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

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

\( \lambda \) – specific heat conductivity [W/(m·K)]

\( \delta \) – heat path [m]

\( \vartheta_{at} \) – ambient temperature [°C]

\( A \) – surface of the thermocouple [m²]

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 \( \varnothing d_{\text{pipe}} = 40 \text{ mm} \) consisting of three parts was used: The supply pipe was \( l_{\text{sup}} = 1100 \text{ mm} \), the sensor pipe \( l_{\text{sens}} = 100 \text{ mm} \) and the effuser \( l_{\text{eff}} = 200 \text{ mm} \) long. A ventilator (SEPA MFB40D-12H) generated an air flow between \( v_{\text{min}} = 0.25 \text{ m/s} \) and \( v_{\text{max}} = 1.23 \text{ m/s} \). 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. For the filament the intention was to generate square heat 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 \( \Delta x_1 = 5.5 \text{ mm} \), from the first TC to the second TC \( \Delta x_2 = 19.5 \text{ mm} \), and from the second TC to the third TC \( \Delta x_3 = 19.1 \text{ mm} \). The filament and the TCs were vertically plugged \( y = 5.9 \text{ mm} \) 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.

\[
\dot{Q}_{th} = \alpha \cdot A \cdot \Delta \vartheta \cdot \Delta t \quad (3)
\]

\( \alpha = \frac{2 \cdot Nu}{L} \quad (4)
\]

\[
Nu = 0.0664 \cdot (Pr)^{\frac{1}{3}} \cdot (Re)^{\frac{1}{2}} \quad (5)
\]

\( Q_{th} \) – heat convection energy [Ws]

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

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).
\[ \alpha = \text{heat transfer coefficient [W/(m}^2\cdot\text{K}]} \]
\[ A = \text{heating surface [m}^2\] \]
\[ \Delta \theta = \text{temperature difference [K]} \]
\[ \Delta t = \text{time difference to traverse the contemplated surface (dependent on velocity) [s]} \]
\[ L = \text{width of the filament [m]} \]
\[ \text{Pr} = \text{Prandtl number} \]
\[ \text{Re} = \text{Reynolds number} \]
\[ \text{Nu} = \text{Nusselt number} \]
\[ \eta = \text{mean velocity [m/s]} \]
\[ \rho = \text{density [kg/m}^3\] \]
\[ \lambda = \text{thermal diffusivity (}\lambda/(c_p \rho)\text{) [m}^2\text{/s]} \]
\[ \nu_m = \text{velocity [m/s]} \]
\[ \eta = \text{dynamic viscosity [kg/(m} \cdot \text{s}]} \]
\[ \lambda = \text{thermal diffusivity (}\lambda/(c_p \rho)\text{) [m}^2\text{/s]} \]

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

A volume of \( V = 4 \text{ mm}^3 \) of air passes the filament symmetrically (as shown in Figure 5) in a time \( \Delta t \) (dependent on velocity) and with an existing temperature difference of \( \Delta T = 10 \text{ K} \). Table 1 shows the potential heat convection and the differential thermal energy \( \Delta E_{\text{th,air}} \) of the air at the thermocouples.

![Figure 5: A cube of 4 mm³ of air passing the filament.](image)

**Table 1: Potential differential thermal energy at the thermocouples in addition to the velocity by \( \Delta \theta = 10 \text{ K} \).**

<table>
<thead>
<tr>
<th>( \nu_m ) [m/s]</th>
<th>( \Delta E_{\text{TC,1}} ) [J]</th>
<th>( \Delta E_{\text{TC,1}} ) [J]</th>
<th>( \Delta E_{\text{TC,2}} ) [J]</th>
<th>( \Delta E_{\text{TC,3}} ) [J]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>1.122</td>
<td>0.776</td>
<td>0.408</td>
<td>0.254</td>
</tr>
<tr>
<td>0.2</td>
<td>0.793</td>
<td>0.487</td>
<td>0.229</td>
<td>0.136</td>
</tr>
<tr>
<td>0.4</td>
<td>0.561</td>
<td>0.297</td>
<td>0.125</td>
<td>0.072</td>
</tr>
<tr>
<td>0.6</td>
<td>0.458</td>
<td>0.219</td>
<td>0.087</td>
<td>0.049</td>
</tr>
<tr>
<td>0.8</td>
<td>0.397</td>
<td>0.175</td>
<td>0.067</td>
<td>0.037</td>
</tr>
<tr>
<td>1.0</td>
<td>0.355</td>
<td>0.147</td>
<td>0.054</td>
<td>0.030</td>
</tr>
<tr>
<td>1.2</td>
<td>0.324</td>
<td>0.127</td>
<td>0.046</td>
<td>0.025</td>
</tr>
<tr>
<td>1.4</td>
<td>0.300</td>
<td>0.112</td>
<td>0.040</td>
<td>0.022</td>
</tr>
</tbody>
</table>

Table 1 presents that the air heated by the filament contains enough thermal energy to heat up the thermocouples which need \( \Delta E_{\text{th}} = 0.19 \mu J \) (\( \Delta t = 0.05 \text{ mm} \)) by a given distance of nearly \( \Delta x = 50 \text{ mm} \) and a velocity of more than \( \nu_m = 1.4 \text{ m/s} \).

### 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 \( \tau \) between these signals. The mathematical expression of the cross-correlation is given for two different signals \( x(t) \) and \( y(t) \):

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

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:

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

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 \( R_{xy,\text{norm}}(\tau) \) [7]:

\[ R_{xy,\text{norm}} = \frac{R_{xy}(k)}{\sqrt{R_{xx}(0) \cdot R_{yy}(0)}} \quad (10) \]

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 \( \Delta T = 0.1 \text{ K} \) to ambient temperature. The heat transfer results from heat conduction. In addition, a sampling rate of up to \( f_s = 10 \text{ kHz} \) 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 \( v_m = 0.1 \text{ m/s} \).

The heat transfer occurs in a band width of \( \Delta y \approx 5 \text{ mm} - 6 \text{ mm} \) and a length of nearly \( \Delta x \approx 80 \text{ mm} \). 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.**

<table>
<thead>
<tr>
<th>( v_m ) [m/s]</th>
<th>( \Delta T_{TC0} ) [T]</th>
<th>( \Delta T_{TC1} ) [T]</th>
<th>( \Delta T_{TC2} ) [T]</th>
<th>( \Delta T_{TC3} ) [T]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.32</td>
<td>4.1</td>
<td>2</td>
<td>1.4</td>
<td>1.1</td>
</tr>
<tr>
<td>0.43</td>
<td>3.5</td>
<td>1.5</td>
<td>1.2</td>
<td>1.0</td>
</tr>
<tr>
<td>0.57</td>
<td>3.0</td>
<td>1.3</td>
<td>1.1</td>
<td>0.9</td>
</tr>
<tr>
<td>0.70</td>
<td>2.6</td>
<td>1.1</td>
<td>0.9</td>
<td>0.8</td>
</tr>
<tr>
<td>0.82</td>
<td>2.2</td>
<td>1.0</td>
<td>0.8</td>
<td>0.7</td>
</tr>
<tr>
<td>0.95</td>
<td>2.0</td>
<td>1.0</td>
<td>0.8</td>
<td>0.6</td>
</tr>
<tr>
<td>1.08</td>
<td>1.8</td>
<td>1.0</td>
<td>0.7</td>
<td>0.5</td>
</tr>
<tr>
<td>1.20</td>
<td>1.7</td>
<td>0.8</td>
<td>0.6</td>
<td>0.3</td>
</tr>
</tbody>
</table>

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 6: Computed distribution of heat after the filament at a mean velocity of 0.1 m/s; filament (Fi), location of the thermocouples (TC1 – TCIII).](image)

Figure 6: Computed distribution of heat after the filament at a mean velocity of 0.1 m/s; filament (Fi), location of the thermocouples (TC1 – TCIII).

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 \( U \).

![Figure 8: Measured mean velocity to the output voltage applied at the ventilator.](image)

Figure 8: Measured mean velocity to the output voltage applied at the ventilator.
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 $\Delta T = 10$ 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 $\Delta x = 0.02$ 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.

6. REFERENCES


