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# The analysis of thermocouple time constants as a function of fluid velocity

**Abstract**

In steady-state conditions when the fluid temperature is constant, there is no damping and time lag so the temperature measurement can be performed with a high accuracy. But when the fluid temperature is varying rapidly as during the start-up, quite appreciable differences occur between the exact and measured temperature because of the time required for the transfer of heat to the thermocouple placed inside a thermometer pocket. The temperature of the fluid is one of the key parameters affecting the proper operation of thermodynamic cycles, so the precise determination of its value is very important. The speed of the response of control systems to a temperature change is closely related to the time constant of the used thermocouples. The paper presents a significant impact of fluid velocity changes (in this case air) on the value of time constants of thermometers. For this purpose, the experimental study was carried out using sheathed thermometers with different diameters and hot junctions. The time constants determined for various thermometers are compared.

**Keywords**: time constant, thermocouple, transient temperature measurement, experimental analysis.

## 1. Introduction

Temperature is one of the basic thermodynamic parameters of the state. It is related to the average kinetic energy of vibration and movement of the molecules making up the system and is a measure of that energy. It can be precisely specified only for the state of thermodynamic equilibrium since in accordance with the zeroth law of thermodynamics the temperature is the physical quantity which determines the common property of the two systems that remain in the balance with each other. Knowledge of actual and accurate temperature is very important because it significantly influences the course and character of processes occurring in nature. The fluid temperature is also one of the parameters through which the flow of a substance can be described, or efficiency of processes in power plants can be determined.

Most books on temperature measurement concentrate on steady-state measurements of fluid temperature [1-9]. Only a unit-step response of thermometers is considered to estimate the dynamic error of the temperature measurement. Little attention is paid to measurements of transient fluid temperature, despite the great practical significance of the problem [10-12].

A sheathed thermocouple is widely used type of a temperature sensor. The thermocouple consists of two wires, which are made of different materials, joined at one end (junction end or measuring end) and forming a part of a system utilizing the thermoelectric effect to measure temperature [13]. Thermocouples are divided into various types: R, S, B, J, T, E, K, N, due to the different metals used in their construction. Thermocouple wires must be isolated from each other along the entire length except the measuring end. The thermocouple sheath protects the temperature sensor. The main advantages of thermocouples are small size, low heat capacity, wide measurement range, simplicity of construction and high reliability. However, like all real objects, thermocouples have drawbacks, which include instability of the measuring end and the possibility of current flow beyond the thermocouple circumference, which can lead to damage of the temperature sensor, and in extreme cases, to the destruction of computer hardware or problems with the correct operation of the system and its control.

The value of the thermocouple time constant allows determining when the temperature indicated by the measuring system is the actual temperature of the fluid [14]. Knowledge of the thermocouple time constant is also very important for temperature control systems and enables shortening the system response time. In the processes that require maintaining precise temperature of the fluid, the response time of the control system is crucial.

## 2. Methods of determining the thermometer time constant

Usually, the sheathed thermocouple is modeled as an element of the concentrated thermal capacity. It is assumed that the temperature of the thermometer is only a function of time, and temperature differences occurring in the thermometer are omitted. Temperature changes of the thermometer in time $T(t)$ are described by an ordinary first order differential equation (first order thermometer model)

$$\tau \frac{\mathrm{d}T(t)}{\mathrm{d}t} + T(t) = T_f(t), \tag{1}$$

where:

$T$ – temperature indicated by the thermocouple, ºC,
$T_f$ – temperature of the fluid, ºC,
$t$ – time, s,
$\tau = mc/(\alpha A)$ – time constant of the thermocouple, s.

For thermometers with a heavy housing used for measuring the temperature of the fluid under high pressure, the accuracy of the second order model is more adequate [15].

The solution of the differential equation (1) for the initial condition:

$$T(0) = T_0 = 0 \tag{2}$$

is:

$$u(t) = \frac{T(t) - T_0}{T_f - T_0} = 1 - \exp\left(-\frac{t}{\tau}\right), \tag{3}$$

where $u(t)$ – unit step response. The time constant of the thermocouple $\tau$ is a crucial parameter that characterizes this type of a measuring device.

The simplest, but burdened with the greatest error, a way of determining the time constant is a graphical method. It consists in leading the tangent to the curve illustrating the change in temperature indicated by the thermocouple from the time that has passed since a step change in temperature. The period of time from the point of tangency to the intersection of the tangent with a straight drawn through a point corresponding to the temperature of the fluid is the time constant of the thermometer (Fig. 1).

A more accurate method of determining the time constant of the thermometer is an experimental method using the method of least squares. It was used to determine the time constant $\tau$ in Eq. (3). The values for the time constants are found by minimizing the function $S$

$$S = \sum_{i=1}^{N} \left[ u_m(t_i) - u(t_i) \right]^2 = \min, \tag{4}$$

where $u(t)$ is the approximating function given by Eq. (3). The symbol $N$ denotes the number of measurements ($t_i$, $u_m(t_i)$). That is the sum of the squares of the deviations of the measured values

$u_m(t_i)$ from the fitted values $u(t_i)$ is minimized. To eliminate partially random errors from the measurement data, a 9-point digital filter can be applied [4]. Once the time constant $\tau$ has been determined, it can be substituted into Eq. (4) to find the value for $S_{\min}$.

The uncertainty in the calculated time constant $\tau$ is estimated using the mean square error

$$S_N = \sqrt{\frac{S_{\min}^2}{N-m}}\ , \tag{5}$$

where $m$ is the number of time constants ($m = 1$ for Eq. (3)).

Based on the calculated mean square error $S_N$, which is an approximation of the standard deviation, the uncertainty in the determined time constant can be calculated using TableCurve software [16].

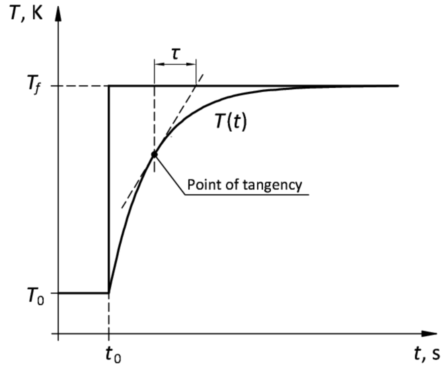

Fig. 1. Graphical method of determining the thermocouple time constant

## 3. Description of the laboratory stand construction

To determine the relationship between the value of the time constant of the sheathed thermocouple $\tau$ and the air velocity $w$, the open benchtop wind tunnel WT4401-D was used (Fig. 2).

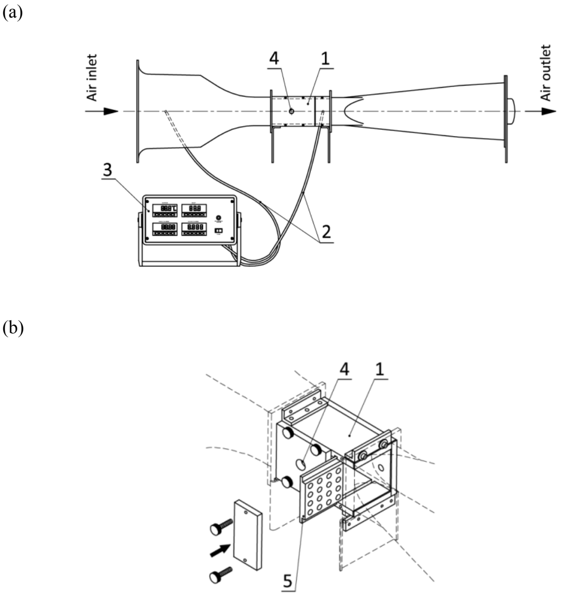

Fig. 2. Wind tunnel used for determining the thermocouple time constant (a) overall view (b) restrictive plate placement [17]: 1 − test chamber with opening for the thermometer; 2 − differential pressure measurement; 3 − recorder, 4 − opening for the thermometer insertion, 5 − restrictive plate for adjusting the velocity measurement range

This tunnel is utilized for calibration of anemometers and allows obtaining a known and steady velocity airflow over 100 mm × 100 mm test cross section. It uses the principle of operation of the Venturi tube where the flow velocity of air is determined by the difference between the pressure measured at the point of the inlet to the tunnel and the point located in the measuring space (Figs 2 and 3).

The laboratory stand also includes a recorder that allows the monitoring of air velocity, ambient temperature, barometric pressure and air humidity. All these parameters have the influence on the pressure difference on the basis of which the air velocity in the tunnel is determined.

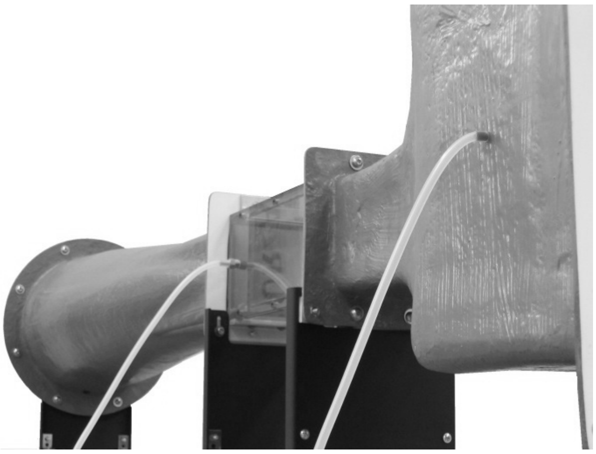

Fig. 3. Location of tubing connections

During the experiments the tested thermometers were heated by a fan heater and then cooled in the measuring space of the laboratory stand at a known velocity of the air. The measurement data was collected using the Ahlborn data acquisition system (ALMEMO 2890-9).

## 4. Analysis of the measurement results

As a result of the experiment time constants of the thermometers with different outer diameters were determined. Tests were carried out on the sheathed thermocouples:

- Fe-CuNi (type J) with diameters: 1, 1.5, 2, 3, 4.5, 6 mm with grounded hot junctions,
- Fe-CuNi (type J) with diameters: 1, 1.5, 2, 3, 4.5, 6 mm with insulated hot junctions,
- NiCr-NiAl (type K) with diameters: 1.5, 3, 4.5, 6 mm with uncovered hot junctions,
- NiCr-NiAl (type K) with diameters: 0.5, 1, 1.5, 3 mm with grounded hot junctions.

For each thermometer, a series of temperature measurements for various velocities of air flowing through a wind tunnel was made. Then, for each air velocity the time constant of the thermometer was determined. The experimental data points collected for each thermocouple were approximated by the least squares method to the following formula [18]:

$$\tau(w) = \frac{1}{a + b\sqrt{w}}\ , \tag{6}$$

where:

$\tau(w)$ – time constant, s,
$w$ – velocity of air, m/s,
$a$ – constant, $\mathrm{s}^{-1}$,
$b$ – constant, $(\mathrm{ms})^{-1/2}$.

The best estimates for the constants *a* and *b*, with the 95% confidence uncertainty in the results are presented in Tab. 1.

Tab. 1. Calculated values of searched coefficients *a* and *b*

| The diameter of the sheathed thermocouple | Value of coefficients $a \cdot 10^{-2}$, $s^{-1}$ | Value of coefficients $b \cdot 10^{-2}$, $(ms)^{-1/2}$ |
|---|---|---|
| Fe-CuNi (type J) thermocouple with grounded hot junction | | |
| 1.0 mm | 1.83± 0.5 | 12.7± 0.7 |
| 1.5 mm | 1.07 ± 0.1 | 6.80 ± 0.2 |
| 2.0 mm | 0.467 ± 0.08 | 4.86 ± 0.1 |
| 3.0 mm | 0.301 ± 0.06 | 2.71 ± 0.1 |
| 4.5 mm | 0.234 ± 0.09 | 1.27 ± 0.08 |
| 6.0 mm | 0.154 ± 0.08 | 0.863 ± 0.08 |
| Fe-CuNi (type J) thermocouple with insulated hot junction | | |
| 1.0 mm | 3.49 ± 0.7 | 9.02 ± 0.8 |
| 1.5 mm | 1.44 ± 0.4 | 6.42 ± 0.6 |
| 2.0 mm | 1.08 ± 0.1 | 3.77 ± 0.2 |
| 3.0 mm | 0.319 ± 0.1 | 2.54 ± 0.2 |
| 4.5 mm | 0.14 ± 0.1 | 1.43 ± 0.1 |
| 6.0 mm | 0.191 ± 0.06 | 0.850 ± 0.06 |
| NiCr-NiAl (type K) thermocouple with uncovered hot junction | | |
| 1.5 mm | 0.696 ± 0.6 | 10.2 ± 0.9 |
| 3.0 mm | 0.298 ± 0.1 | 2.98 ± 0.2 |
| 4.5 mm | 0.0857 ± 0.2 | 1.95 ± 0.2 |
| 6.0 mm | 0.0365 ± 0.04 | 1.12 ± 0.2 |
| NiCr-NiAl (type K) thermocouple with grounded hot junction | | |
| 0.5 mm | 0.434 ± 0.06 | 2.22 ± 0.1 |
| 1.0 mm | 2.1 ± 0.6 | 10.4 ± 1.0 |
| 1.5 mm | 4.04 ± 0.3 | 5.69 ± 0.4 |
| 3.0 mm | 12.8 ± 4.0 | 22.1 ± 5.0 |

The time constant values obtained experimentally and the graph of Eq. (6) for a J-type thermocouple with insulated junction end with a diameter of 2 mm are shown in Fig. 4.

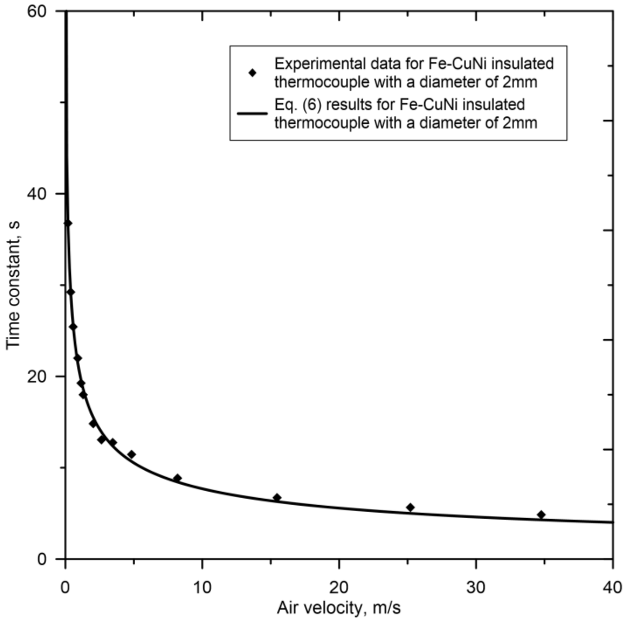

Fig. 4. Time constants *τ* of a J-type sheathed thermocouple with insulated junction end with the outer diameter of 2.0 mm as a function of air velocity *w* with 95% confidence interval limits

The time constants of different types of thermocouples with an outer diameter of 1.5 mm having different measuring ends are shown in Fig. 5.

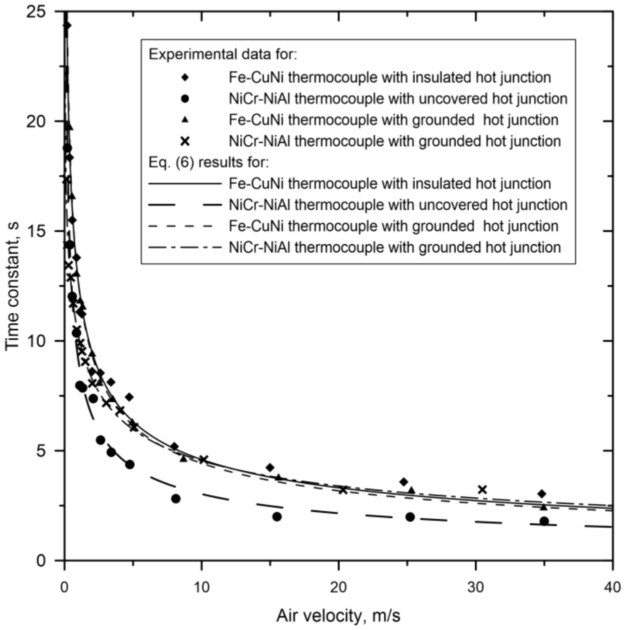

Fig. 5. Time constants *τ* of J-type sheathed thermocouple with grounded junction end, J-type sheathed thermocouple with insulated junction end, K-type sheathed thermocouple with uncovered junction end and K-type sheathed thermocouple with grounded junction end with the outer diameter of 1.5 mm as a function of air velocity *w*

The next diagram (Fig. 6) shows the difference between the time constants of J-type sheathed thermocouples with insulated junction ends with outer diameters: 1, 1.5, 2, 3, 4.5, 6 mm as a function of the air velocity.

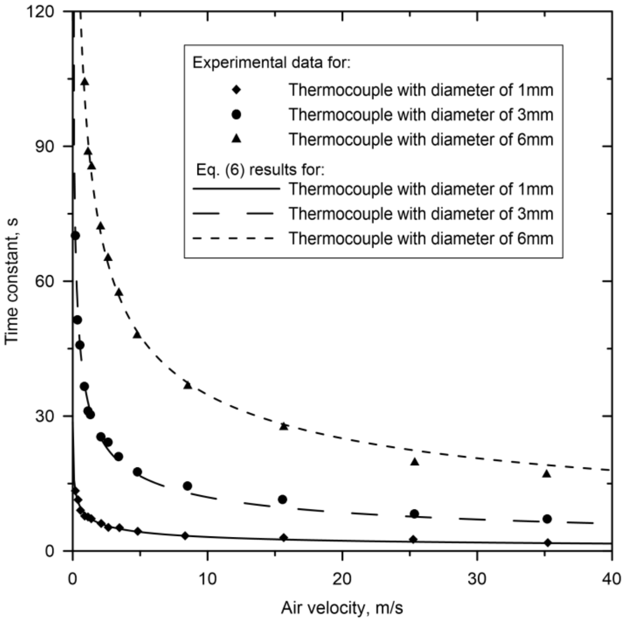

Fig. 6. Time constants τ of J-type sheathed thermocouples with insulated junction ends with outer diameters of 1, 1.5, 2, 3, 4.5, 6 mm as a function of air velocity *w*

The obtained results show that the fluid velocity significantly affects the time constant of the thermometer (Figs. 4-6). Also the construction of thermometers has the impact on the value of the time constants (Fig. 5). The highest values of the time constants were obtained for the thermocouples with insulated hot junction, slightly smaller for the thermocouples with grounded hot junction. The considerably lower time constants values were obtained for the thermometers with uncovered junction end.

## 5. Conclusions

The method presented in this paper for measuring the transient temperature of a fluid can be used for the on-line monitoring of fluid temperature change in time. This method, where the thermometer is modeled using an ordinary first-order differential equation, is appropriate for thermometers that have small time constants. In such cases, the thermometer delay is small in comparison to the changes of the fluid temperature. When the thermometer delay is big, it is more appropriate to consider the thermometer as a second-order inertia device. Substantial stability and accuracy of the computed actual fluid temperature from the measured thermometer temperature can be achieved by using a 9-point digital filter. The technique proposed in this paper can also be used when the thermometer time constant is a function of fluid velocity.

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