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DETERMINING THE TIME CONSTANT USING TWO METHODS AND DEFINING THE THERMOCOUPLE RESPONSE TO SINE EXCITATION OF GAS TEMPERATURE

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Abstract

This paper describes the two methods of determining the time constant of type K thermocouple, for two construction solutions: the exposed weld and the mantle fillet weld. This is an important parameter indicating the response time of the thermocouple on the recorded signal. The first method consists of determining the value of τ in the way of numerical simulation of heat exchange between the thermocouple and the current of gas [2] for the parameters adopted for the gas and for the known construction of the temperature sensor. The second method is a graphical determination of these parameters on the basis of the sequence of high frequency temperature of gas. The study was conducted to determine the position of the dynamic properties of thermocouples [3]. Based on these results was made the choice of the thermocouple with the best dynamic properties, which helped during the tests on the reciprocating compressor [4]. On the basis of the sequence of high frequency temperature and gas pressure was determined the response of the thermocouple on the sine excitation of gas temperature (the phase and amplitude displacement of the sequence) [5]. The used method of signal correction was rated and its suitability for diagnostic testing of piston machines was determined.

Keywords: piston compressor, gas temperature measurement, diagnostics, time constant of the thermocouple.

1. Introduction

Parametric diagnostic of piston machines is an important subject of modern engineering. Aiming to create a method of diagnosing the workspace of these instruments during their usage (using the measurements of high frequency temperatures) it is necessary to create a tool which serves to process and interprete the signals acquired during the research. Determining the constant time value is a tool which allows the appropriate choice to be made for given measurement conditions [2]. Depending on the parameters of the flowing gas (e.g. temperature, speed, chemical constitution) and on the required measuring accuracy (τ between a few and a few dozen ms), an optimal choice should be made. Determining the actual sequence of gas temperature using the phase and amplitude shift of the thermocouple signal, allows the correct interpretation of the received research results, which ultimately leads to defining the diagnostic method.

2. Determining the time constant of type K thermocouple

2.1 Determining the time constant by way of numerical simulation

A numeric simulation of heat exchange between a diagnostic weld and the gas (air) circulating it was conducted for two constructional solutions for type K thermocouple. Considered in the calculations were thermocouple with an exposed weld in a ceramic casing (fig. 1) and thermocouple with a mantle fillet weld in a inconell casing (fig. 2). Time constant values were determined for both thermocouples, with the calculations using the input data presented in tables 1 and 2. The full algorhythm of these calculations was covered in [2] article, and as such only dependencies used to calculate the time constant values were presented.

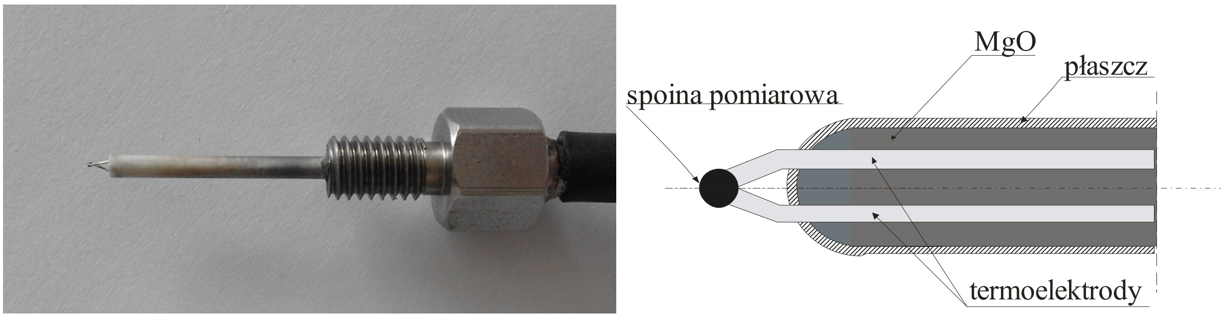

Fig. 1 The view and schematic of type K thermocouple with an exposed weld

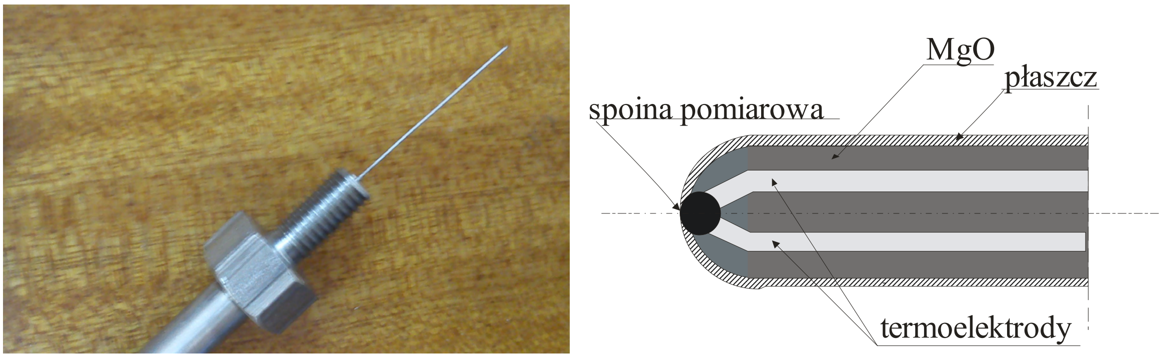

Fig. 2 The view and schematic of type K thermocouple with a mantle fillet weld

Time constant for a thermocouple with an exposed weld:

$$\tau = \frac{C_{nicr}}{A_{nicr} \cdot \alpha_{wp}}[s] \tag{1}$$

where: C_{nicr} – thermal capacity of the measuring junction [J/K]

A_{nicr} – surface of the measuring junction [m^2]

α_{wp} – conventive heat-transfer coefficient [W/m^2K]

Tab. 1 The values adopted for the calculation of the time constant of the thermocouple with an exposed weld

1. Given values:
c=1m/s - gas velocity
$t_{pow}=140^{o}C$ - gas temperature (average)
d=0,0002m - diameter of the measurement weld
l=0,02m - length of the thermocouple
d_{char}= 0,0002m - characteristic dimension
2. Table values:
Air data:
ρ_{pow}=0,854 kg/m^3 - density of air
η_{pow}=0,0000237 kg/m•s - absolute viscosity of air
c_{pow}=1013 J/kg•K - specific heat of air
λ_{pow}= 0,0349 W/m•K - heat conductivity of air
Weld material data:
c_{pnicr}=444 J/kg•K - specific heat of NiCr
ρ_{nicr}=8666 kg/m^3 - density of NiCr

Time constant for a thermocouple with a mantle fillet weld:

$$\tau = \frac{C_p}{A_{zp} \cdot \alpha_{wp}} [s] \tag{2}$$

where: C_p – thermal capacity of inconell [J/K]

A_{zp} – surface of the mantle [m^2]

α_{wp} – convective heat-tranfer coefficient [W/m^{2}K]

Tab. 2 The values adopted for the calculation of the time constant of the thermocouple with a mantle fillet weld

1. Given values:
c=1m/s - air velocity
$t_{pow}=325^{o}C$ - air temperature
l=0,02m - length of thermocouple
d_{zew}=0,0005m - outer diameter of the mantle of the thermocouple
d_{wew}=0,0003m - inside diameter of the mantle of the thermocouple
d_{char}= 0,00075m - characteristic dimension

2. Table values:
Air data:
ρ_{pow}=0,591 kg/m^3 - density of air
η_{pow}=0,00003055 kg/m•s - absolute viscosity of air
c_{pow}=1053 J/kg•K - specific heat of air
λ_{pow}= 0,0574 W/m•K - heat conductivity of air
Mantle material data: inconell 600 alloy:
c_{pin}=461 J/kg•K - specific heat of inconell
ρ_{in}=8510 kg/m^3 - density of inconell

Based on the input data presented in tables 1 and 2 (respectively for thermocouples with an exposed weld with a ceramic casing and for thermocouples with a mantle fillet weld made of inconell) and the known calculation algorithm [2] the time constant values were determined for both the heat sensors. The results of these calculations are presented in table 3 of this article, and the conclusions pertaining to the time constant values are presented in section 2.3.

2.2 Determining the time constant based on the results of empirical research

2.2.1 Research station

In order to determine time constant values for both the construction solutions for the thermocouple, empirical research was conducted on a station which resembled a simplified physical model of the exhaust phase of a compression-ignition engine. The station was built as a part of the doctorate of the author of this article, in order to research the dynamic qualities of thermocouples. The view of the station is presented in figure 3 while the details of its build and performance are elaborated on in the [3] article.

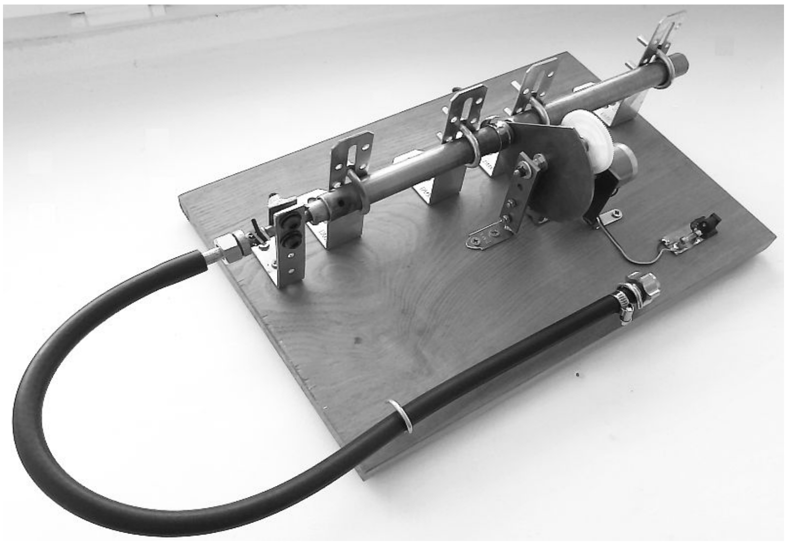

Fig. 3 Research station for the dynamic qualities of thermocouples [3]

On the station research was conducted using both thermocouples described previously in section 2.1, with the goal of comparing the time constant values for both the sensors and, consequently, choosing the solution with the best dynamic qualities.

2.2.2 Time constant calculations

After conducting the empirical research on the test station (fig. 3), high frequency temperature profiles in a time function were designated for both thermocouples. Based on those profiles were determined the time constants which align with the algorithm described below. Fragments of the profiles were depicted in graphic form (shown in figures 5 and 6) and used for determining the time constants.

Consistent with the interpretation of the time constant being the time in which the excess heat of the sensor exceeds the initial temperature by 0.632 of the initial excess temperature [5], it is possible to determine it in a graphical way (fig. 4):

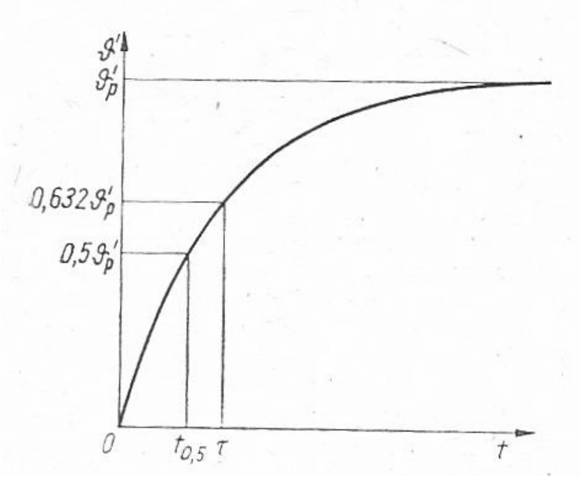

Fig. 4 The response of the heat sensor whose parameters are focused on a step function and the interpretation of the time constant [5]

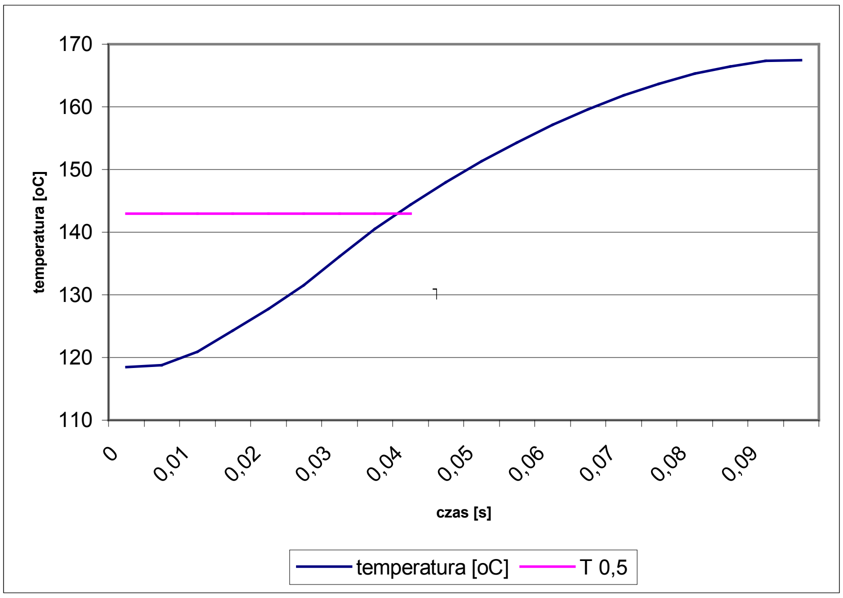

Fig. 5 Gas temperature profile obtained during the measurement using the thermocouple with an exposed weld, stressing the temperature $T_{0,5}$ used for determining the time constant of the thermocouple

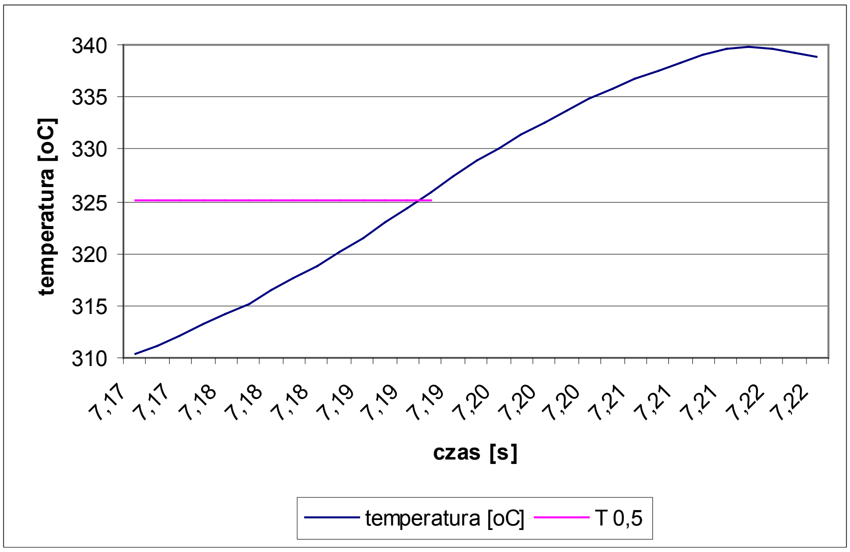

Fig. 6 Gas temperature profile obtained during the measurement using the thermocouple with a mantle fillet weld, stressing the temperature $T_{0,5}$ used for determining the time constant of the thermocouple

Another possibility to determine the time constant is to determine the time $t_{0.5}$ of half-value after which the sensor reaches the excess temperature equal to half of the starting excess. This method was used during the determination of the time constant from pre-existing high frequency temperature profiles. The time constant is then calculated using the following correlation [5]:

$$\tau = \frac{t_{0,5}}{\ln 2} = \frac{t_{0,5}}{0,693} \tag{3}$$

The time constant values for both thermocouples determined using the described test method is presented in table 3 of this article, while the findings pertaining to the choice of the thermocouple used in subsequent research is presented in section 2.3.

2.3 The choice of the thermocouple used in subsequent research, based on the results of calculations

In table 3 presented are the time constant values determined using the aforementioned methods. As a result of the simulatory calculations based on the method using the heat exchange between the measuring junction and the flowing gas, it was proven that the time constant of the thermocouple with the exposed weld has a lower value than the time constant of the isolated weld thermocouple. It is a dependency true to the available data, pointing to a shorter reaction time of the thermocouple whose measuring element is exposed. In the case of the laboratory station research, the resulting correlation was reversed, which might have been caused by several factors, including, e.g.: varying conditions of measurement (gas temperature, gas flow velocity, measurement conditions, etc.) or a higher measuring error than in the case of the first method. The value of the time constant is also noticeably higher using the simulatory method, compared to what was established using the theoretical research (despite the input values being similar in both cases). This discrepancy may be the result of varying input parameter values – parameters of the gas defined in the simulation may diverge from those of the fluid tested at the research station. This inclines further development of both of the measuring methods for the time constant values of type K thermocouples.

Tab. 3 Time constant values determined using the two methods for varying constructional solutions of the thermocouple

	Time constant - research [ms]	Time constant - simulation [ms]
Exposed weld thermocouple	58	215
Fillet weld thermocouple	31	272

Despite the ambiguous results of the time constant calculations, decision was made to use the exposed weld thermocouple for subsequent research. According to both literature [5] and the numerical simulation results, it demonstrates a stronger dynamic (smaller reaction time to temperature changes) as well as satisfactory durability (the weld is exposed, however its diameter is high enough to resist damage during tests using a piston compressor and a CI engine).

3. Defining the response of the thermocouple to sine excitation of gas temperature

3.1 The method of defining the response of the thermocouple

Considering the dynamic of the measurement of the high-frequency gas temperature, the inertness of the entire data transmission system (transistor, measurement card, etc.) should be taken into account. Applying the appropriate calculation formulae [5] makes it possible to indicate the phase shift of temperature changes registered by the thermocouple, in comparison to the actual temperature changes of the exhaust gas [1].

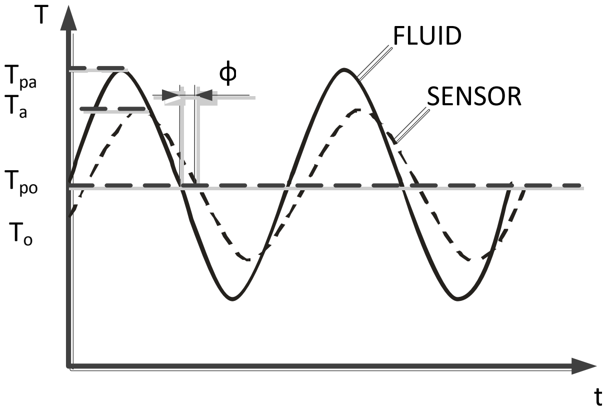

Fig. 7 The response of the temperature sensor whose parameters are focused on the sine excitation of the fluid temperature. (T_o – starting temperature of the sensor, T_a – temperature change amplitude of the sensor, T_{pa} – temperature change amplitude of the medium, T_{po} – starting temperature of the fluid (for T_{po}=const – average temperature))

A vital element during the appraisal of the dynamic properties of the thermocouple is to define the response of the thermocouple (treated as a dynamic member with focused parameters) on the sine excitation of the gas temperature – the phase shift as well as the temperature change amplitude registered by the thermocouple in relation to the forced, actual changes of the gas temperature – fig. 7.

True to the above statement, the actual gas temperature is:

$$T = T_{po} + T_a \cdot \sin[\omega \cdot t + \varphi] \tag{4}$$

The temperature change amplitude of the sensor is:

$$T_a = \frac{T_{pa}}{\sqrt{1+\omega^2 \cdot \tau^2}} \tag{5}$$

While the phase shift of the temperature changes of the sensor, in relation to the temperature changes of the medium is:

$$\varphi = -arctg(\omega \cdot \tau) \tag{6}$$

where:
t – time
T – sensor temperature (actual)
T_a – temperature change amplitude of the sensor
T_{pa} – temperature change amplitude of the medium
T_{po} – starting temperature of fluid (for T_{po}=const – average temperature)
τ – time constant
ω – fluctuation of temperature

3.2 Determining of the actual course of the high-frequency temperature changes of gas

3.2.1 Research station

In order to gain diagnostic information about the technical state of the construction elements which restrict the workspace of the air compressor, a laboratory station was built to research the thermal flow processes in piston machines [4]. The main element of the station is a piston, two-stage air compressor, Espholin H3S with an intercooler. The station was modernized by decreasing the diameter of the belt pulley on the electric motor, in order to decrease the rate of rotation of the air compressor. As a result of the modernization, the accuracy of the acquired high-frequency temperature data using the available measuring apparatus has increased. The most significant parameters of the compressor run are compiled in table 4 while the view of the station is shown in figure 8.

Tab. 4 The parameters of the Espholin H3S air compressor

PARAMETER	VALUE
Rate of rotation	12,5 s^{-1} / 5 s^{-1} (after modernization)
Volumetric efficiency	425 dm^3/min (0,00708 m^3/s)
Effective production output	305 dm^3/min (0,00508 m^3/s)
Electric motor power	5500 W
Outer circumference of the internal thread	0,5”

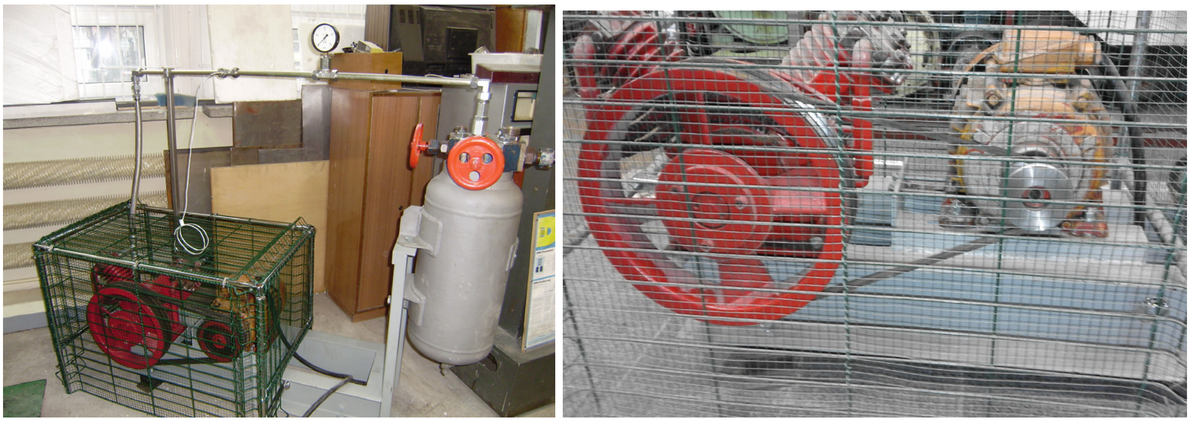

Fig. 8 Research station of the piston compressor before and after the modernization – the change of the drive wheel of the electric motor

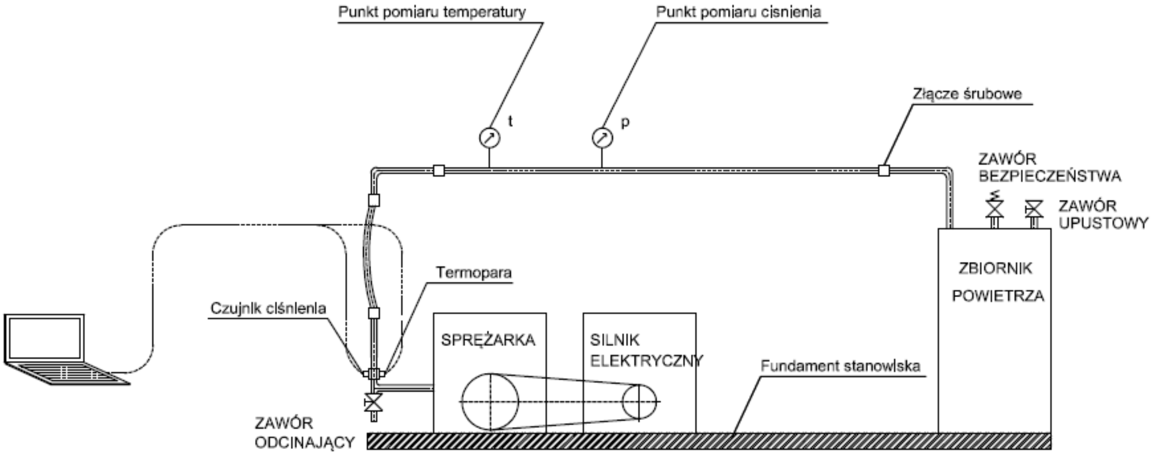

Fig. 9 Diagram of the piston compressor station highlighting the gas temperature and pressure measuring point

To measure the temperature, type K thermocouple with an exposed weld (described in section 2.1 of this paper) as well as pressure sensor (Optrand) were used. As seen in figure 9, the pressure and temperature measurement takes place in the same point of the measuring flume, directly behind the second stage of compression, in order to minimalize the impact of outside factors on the result of the tests. Both of the sensors are connected to the data transmission system, allowing for the registration and subsequent handling of the measurement results.

3.2.2 Determined gas temperature profile

During the tests conducted on the research station described in section 3.2.1, the course of temperature and pressure was acquired, as shown in figure 10. A considerable deceleration of the temperature signal in relation to the pressure is visible, which is the response of the thermocouple on the excitation of the gas temperature. The next step was to define the time constant of the employed thermocouple for the existing measuring conditions, using the method described in section 2.2.2. The time constant was 19.24ms. Next, the course of the gas temperature was determined, taking into account the phase shift and temperature change amplitude registered by the thermocouple in relation to the forced, actual changes of gas temperature, following the algorithm depicted below (fig. 11).

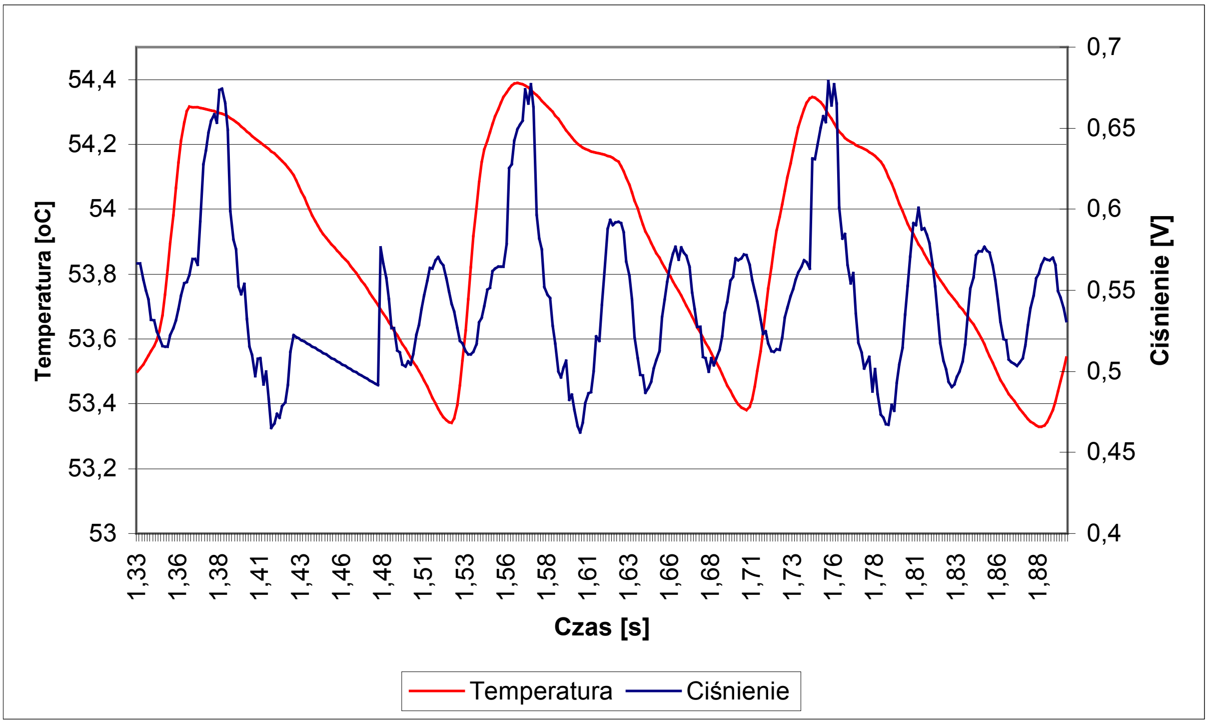

Fig. 10 The course of temperature shown by the temperature sensor and pressure in time function

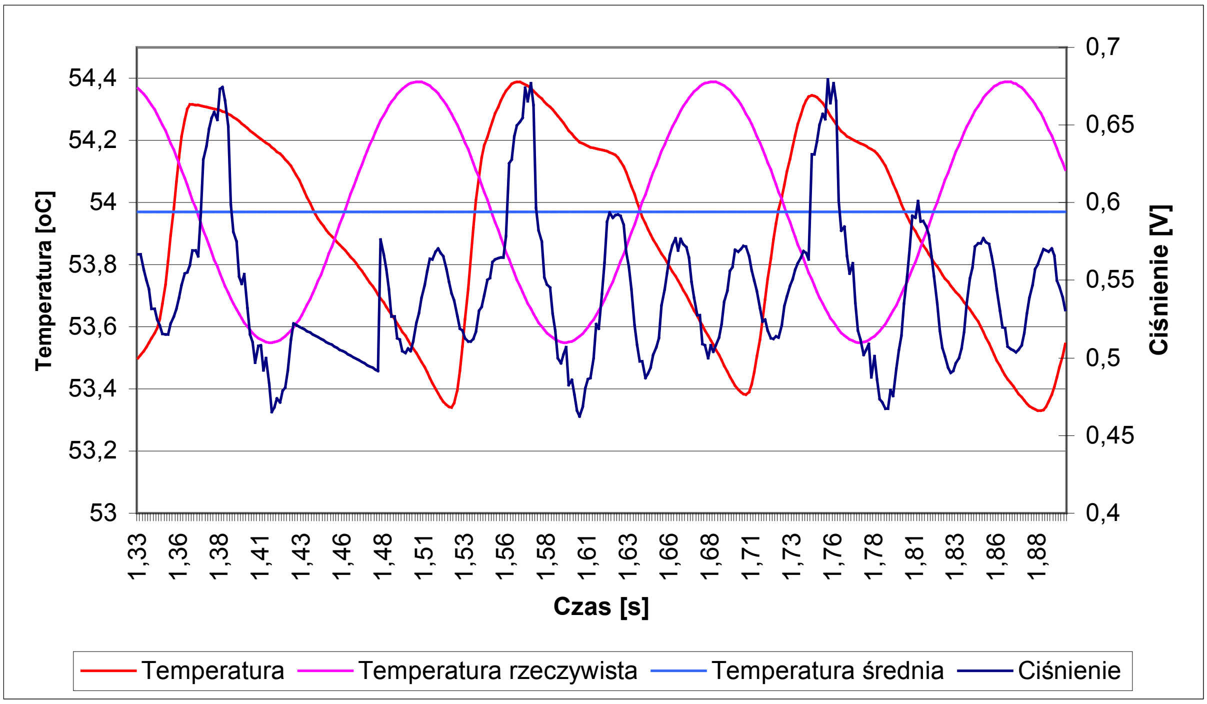

Fig. 11 The course of temperature shown by the temperature sensor and the actual temperature of fluid and pressure in time function

4. Conclusions regarding the research and calculation results

From the results of the time constant calculations for both of measuring methods employed during the research, it can be concluded that the thermocouple using the exposed weld is characterised by greater dynamic properties (which is in line with the literature [5]). It is also evident that the delayed registration of the thermal signal in relation to pressure, measured at the same point of the discharge channel behind the second stage of compression inside of the piston air compressor. This delay is a result of the thermocouple response on the sine excitation of the gas temperature, mentioned above. Using the applied method to offset the signal received from the thermocouple, it was possible to determine the amplitude and phase shift of the temperature recorded by the thermocouple in terms of actual gas temperature. The temperature profile is similar to the actual pressure signal, but the profiles do not overlap, indicating a limitation of the applicability of the algorithm used. In conclusion, the method requires further development before it can be recognized as sufficient for future diagnostic research on the workspace of piston machines.

5. Summary

The applied methods of defining the time constant – both as a form of numerical simulation, when the only known properties are those of the thermocouple and the gas washing over the thermocouple, as well as the high-frequency temperature profile acquired during the empirical research – can be concluded as correct and useful in defining of dynamic properties of thermocouples. Also the method of determination of the actual temperature of the gas, taking into account the phase and amplitude of a signal received from a thermocouple, is appropriate, however, it requires further work to allow its use in conducted research. All of these methods can be used as tools for interpreting and processing the signals received during testing workspaces of piston machines (compressors and motors), where the high-frequency temperature measured in the gas discharge channel is treated as a diagnostic parameter. This allows for further planning of empirical research seeking to develop a method of diagnosing the workspaces of piston machines in operation by measuring high-frequency temperatures of exhaust gases by the author of this paper.

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