Journal of Polish CIMEEAC
Faculty of Ocean Engineering & Ship Technology
GDAŃSK UNIVERSITY OF TECHNOLOGY

A LABORATORY STAND FOR THE ANALYSIS OF DYNAMIC PROPERTIES OF THERMOCOUPLES

Konrad Marszałkowski
Patrycja Puzdrowska

Gdansk University of Technology
Faculty of Ocean Engineering and Ship Technology
Department of Ship Power Plants
11/12 Narutowicza Street 11/12, 80-233 Gdansk
e-mail: konmarsz@pg.gda.pl, patpuzdr@pg.gda.pl

Abstract

In the present elaboration, problems connected with measurements of high variable temperatures of gases are introduced and the impact of dynamic properties of different construction solutions of thermoelements on the accuracy of the measurements is considered. A laboratory stand built within research under doctoral thesis, destined for analysis of dynamic properties of thermocouples is also described. Results of numerical simulation of heat exchange between thermocouple and the gas that washes it (in this case - hot air) is presented as well as results of empirical experiments conducted on the laboratory stand built with the analysis of the obtained results.

Key words: *heat flow processes, measurement of gas temperature, parametric diagnosis.*

1. Introduction.

Planned research of heat flow procceses in exhaust channel of piston machines (air compressor and ship engine) are oriented on diagnostic issues. Their main aim is to elaborate the methodology of assessment of technical state of elements that limit the working space of these machines, based on parameters of state of thermodynamic factor observed in the exhaust channel, where appriopriate gas parameters will be measured, what is determined by limited capability of control of piston machine during its current expoitation. To realize the research goal, it was neccesary to built and equip the laboratory stand, enabling to conduct the experimental research in the conditions close to working conditions of the real object. Measurements of high variable pressures and temperatures of exhaust gases, which were conducted on engines and piston compressors, enable to distinguish several crucial metrological problems that should be forseen while planning the experimental research, both on laboratory stand and while diagnostics of real objects. Among most important ones are: inertia of temperature sensors and the impact of external factors on the result of measurement. Proper selection of methods and measurement tools however enable to minimalize most of the inconsistencies that occur during the measurement of high variable temperatures. Regarding significant difficulty of interpretation of measurements results (disturbed by the above mentioned factors) obtained during the research on laboratory stands of real piston machines, it was decided to simplify the object of consideration. A laboratory stand was built to analyse the dynamic properties of thermocouples, which is the physical model of diesel engine, a tool enabling to improve the research method within heat flow processes taking place in piston machines, what will in fact enable to minimalize the impact of the above mentioned factors on the results of the measurements.

2. Problems related to the measurements of high variable temperature of gases as a diagnostic parameter.

During conducted measurements of high variable temperatures of gases on the laboratory stands of Espholin H3S pistion air compressor and the Farryman diesel engine, numerous metrological problems both within the temperature sensor, measurement signal converter and the disturbances conducted by the environment of measurement could be detected. In order to elaborate the efficient diagnostic method of heat flow system, based on the measurements of gas temprerature flowing with high velocity, it is neccessary to analyse the impact of factors disturbing the measurement and elaborate the method of its minimalization.

One of main disturbances having considerable impact on the accuracy of obtained results of measurements of gas temprerature is the inertia of the used measuring sensor. Most often used to this kind of measurements are thermocouples type K (chromel-alumel), which are made of measurement element with the sheath or without it. In order to inertia of the measurement be the lowest, it is neccessary to apply the thinest measuring element possible, considering the decrease of resistance to damages and durability (being further problems in this measurement method) together with the decrease of a diameter. The sensor without the sheath of measuring element has also significantly lower durability as well as lower inertia. The value determining the inertia of the thermocouple is its time constant dependent on: its size and mechanical construction of thermoelement, thermophysical properties of applied material, thermodynamical properties and character of gas flow. Despite the determination of time constant value by the producers of measuring elements, there is still a need to calibrate the sensor. Significant factor having impact on the accuracy of the measurements of high variable temperatures is the mode of sensor installation. Main obstacle is heating of the thermocouple from the flowing channel material (or other supporting element), into which it is screwed or soldered during the measurement. It has a critical influence on the results of measurements. The only method of mitigation or prevention of this type of disturbance is the efficient insulation of the sensor, f.i. applying of the cooling sheath or the sheath isnulated with ceramic material. First solution is connected with the possibility of leaks occurance and inflow of water into the flowing channel, both methods however increase the cost and the accuracy of the measurements.

Regarding the neccesity of elaboration of the methodology of minimalization of the impact of the mentioned factors with simultaneous maintenance of simplicity and access to the proposed method od measurements, a laboratory stand was built to conduct research on dynamic properties of thermocouples, being the physical model of combustion engine with rotational speed of 480 rev/min, where the measurements of high variable temperature of hot gas with the use of thermocouple type K (selection of which is justified in the below point of the article).

3. Selection of a thermocouple to measurements of high variable temperatures of gases.

In order to obtain the highest diagnostic information of high variable temperature of gases, it is neccessary to select the optimal measurement tool, within the discussed case of the thermocouple [2].

Selecting the structural material of thermo electrodes used in the thermocouple should ensure the highest possible measuring sensitivity. It is possible due to the use of low-resistance materials which allow high thermoelectric voltage to be generated. In the reported case, after thorough analysis of the available offers a decision was made to use a sheathed thermocouple type K (NiCr-

Ni) type, with sheath diameter of 0,5 mm and thermo electrode diameter of 0,1 mm. The insulating material is most often the ceramic powder MgO, while the structural material of the sheath is the nickel-chromium alloy Inconell, which reveals high resistance to corrosion, in particular stress corrosion. This material ensures long lasting operation of the thermocouple up to the temperature of 1100 K, without catalytic reaction to the exhaust gas. The thermometric (voltage) characteristic of the NiCr-Ni thermoelement is linear and sufficiently steep within the used measuring range.
Most producers offer three versions of sheathed thermocouples which differ by the response delay time to the set fluid temperature excitation. Structurally, these thermocouples have: (1) the weld insulated from the sheath (Fig. 1), (2) the weld welded to the sheath (Fig. 2), and (3) the open weld (Fig. 3). However, technical specification of the thermocouple does not specify flow conditions, determined by the type and velocity of the flowing medium, to which this delay time relates. In this situation, dynamic properties of the thermocouple used in quick - changing engine exhaust gas temperature measurements should be determined analytically.

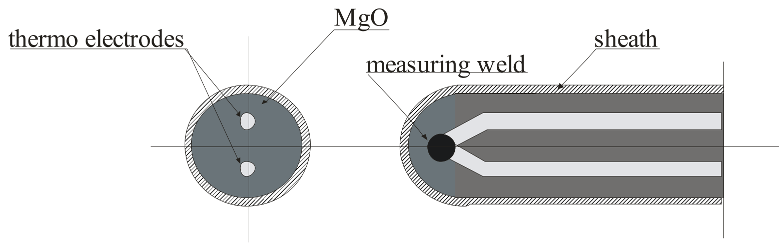


Fig. 1. Longitudinal and cross section of the final part of the sheathed thermocouple with the weld insulated from the sheath

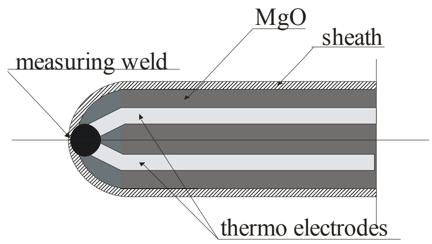


Fig. 2. Longitudinal section of the final part of the sheathed thermocouple with the weld welded to the sheath

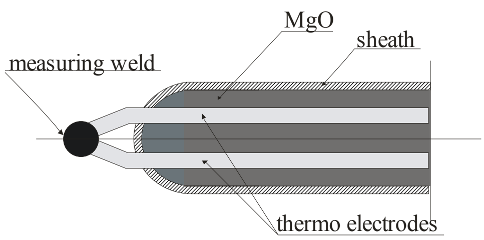


Fig. 3. Longitudinal section of the final segment of the sheathed thermocouple with open weld

The thermocouple with the weld insulated from the sheath is the second order inertial term, and its time constant is described by the equation:

$$\tau_{cz} = \sqrt{\frac{C_{pi}}{A_{zp} \cdot \alpha_{wp}} \cdot \frac{C_{te}}{A_{te} \cdot \frac{1}{R_{\lambda p}}}} \tag{1}$$

A_{zp} – outer surface of the sheath flowed round by the exhaust gas,
A_{te} – total surface of thermo electrodes in the measuring section of the thermocouple,
α_{wp} – thermal transmittance between the exhaust gas and the sheath,
$R_{\lambda p}$ – averaged specific resistance of heat conduction by the sheath and the insulating material:
C_{pi} – total thermal capacity of the constructional material of the sheath and insulation
C_{te} – total thermal capacity of the constructional material of the thermo electrodes

When analysing dynamic properties of the thermocouple with the weld welded to the sheath the time constant is described by the formula:

$$\tau_{cz} = \frac{C_p}{A_{zp} \cdot \alpha_{wp}} \qquad (2)$$

C_p – thermal capacity of the constructional material of the sheath

The shortest time of thermocouple response to the set exhaust gas temperature excitation can be obtained using the sheathed structure with open weld. The time constant of the thermocouple is given by the formula:

$$\tau_{cz} = \frac{C_s}{A_s \cdot \alpha_{ws}} \qquad (3)$$

C_s – the thermal capacity of the measuring weld

The thermal transmittance is determined based on the similarity of heat transfer (penetration) processes, the dimensional analysis (the π theorem formulated by Buckingham in 1924), and experiments. Empirical formulas which are most often used in engineering calculations to determine the thermal transmittance between the thermocouple sheath or the measuring weld (only) and the exhaust gas (in both directions) for the turbulent flow in the channel are given in the following form:

$$\alpha = Nu \cdot \frac{\lambda_{sp}}{d} \qquad (4)$$

λ_{sp} – thermal conductivity of the exhaust gas at given temperature,
d – characteristic linear dimension, for instance the measuring weld diameter,
Nu – Nusselt number, characterising the relation between the heat transfer intensity and the temperature field in the boundary layer of the exhaust gas flow.

4. The laboratory stand for measurement of dynamic properties of thermocouples.

Necessity of calibration of the measurement route with the thermocouple to measure high variable temperatures requires to provide the same thermal conditions as for the exhaust system of diesel piston engine. Previous attempts to build a measurement system were realised with the laboratory single-cylinder diesel engine of brand Farryman and piston air compressor Espholin H3S. In the first case, attempts were quite troublesome, regarding the neccesity to conduct the prototypical research on the measuring devices with the running engine, what makes it dangerous and not always repeatable. In case of research on air compressor [4], impulses of the signal turned out to be too weak to consider their diagnostic value. Because of that reason, it was decided to build a simplified physical model of exhaust phase of diesel engine.

The physical model of the exhaust system was built on the wooden base (pic. 4), to which with the use of four clamps (6), the brazen exhaust pipe (2) of diameter 18/20 mm was installed. At one end of the exhaust pipe the bunsen burner (1) was placed, adjusted to supply with a mixture of propane-butane from typical 2,5 kg gas container. In the place of the burner installation, five holes were made (at the periphery) enabling unconstrained air flow to the inside of the pipe and facilitating burning of the burner without the necessity to take it out from the exhaust pipe. Velocity of exhaust gases is determined by the level of opening of the valve on the gas container, what is dependent on the mode of burner operation.

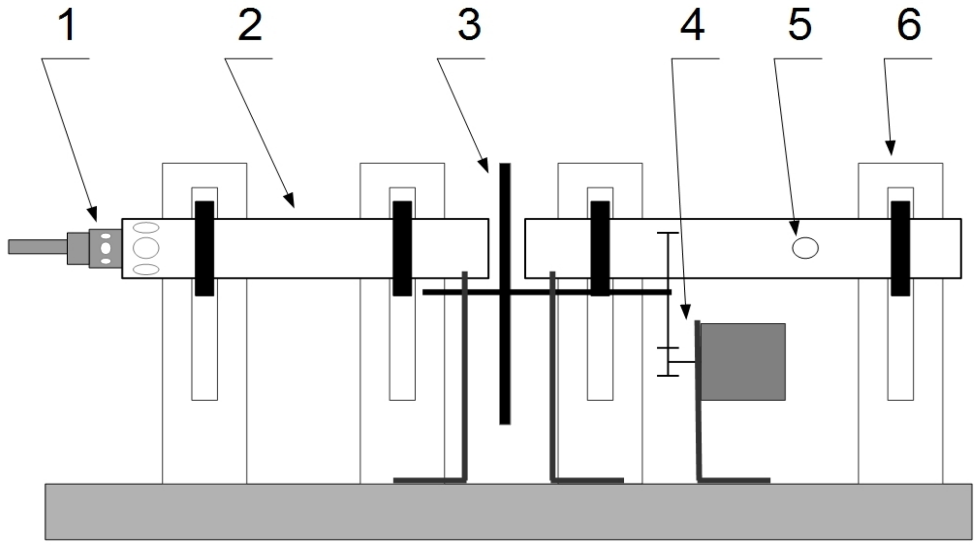


Fig. 4. Physical model of the exhaust system of pistion combustion engine:
1 – gas burner 2 – exhaust pipe 3 – choking throttle 4 – direct current engine with gear
5 – place of thermocouple installation 6 – installation clamps

Exhaust gases are throttled cyclically by the choking throttle (3), which when rotating is covering the exhaust pipe completely and what in simplified mode reflects pressure pulsation in the exhaust collector of piston combustion engine. The throttle is driven by onestep gear with ratio 1:7 from the direct current engine (4). Rotational velocity is regulated by the change of the voltage feeding the engine within the range 0 – 12V , obtaining the maximum rotational velocity of the throttle $n_t = 240\ min^{-1}$, which in case of four-stroke engine gives rotational velocity of crank shaft $n = 480\ min^{-1}$.

Shape of choking throttle and its position with respect to the exhaust pipe is presented in the picture 5.

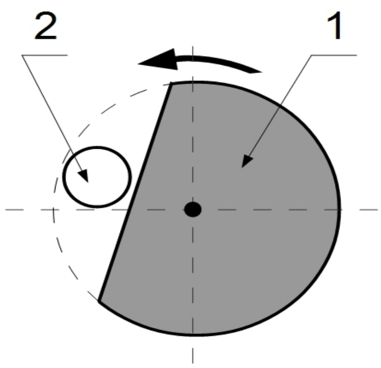


Fig. 5. Shape of choking throttle, where: 1 – choking throttle 2 – exhaust pipe

The exhaust pipe can be moved on installation clamps (6) up and down with respect to choking throttle, thanks to which we can test options of non complete choking of exhaust gases flow.

Thermocouple is experimentally located 40 mm from the end of exhaust pipe (5), as well as at the outlet of the pipe, in the axis of the channel, reffering to maximum amplitude of the thermocouple's signal. It is worth mentioning that the maximum time of measurement, which was obtained with rotational velocity of the choking throttle n_t= 240 min^{-1} is 10s. Aiming to continue the measurements of the thermocouple was to be cooled, as warm measuring tool affected negatively the obtained results. This fact clearly shows the necessity of cooling the sheath as well as the thermocouple itself, in case of realisation of the experiment on the research stand with diesel engine.

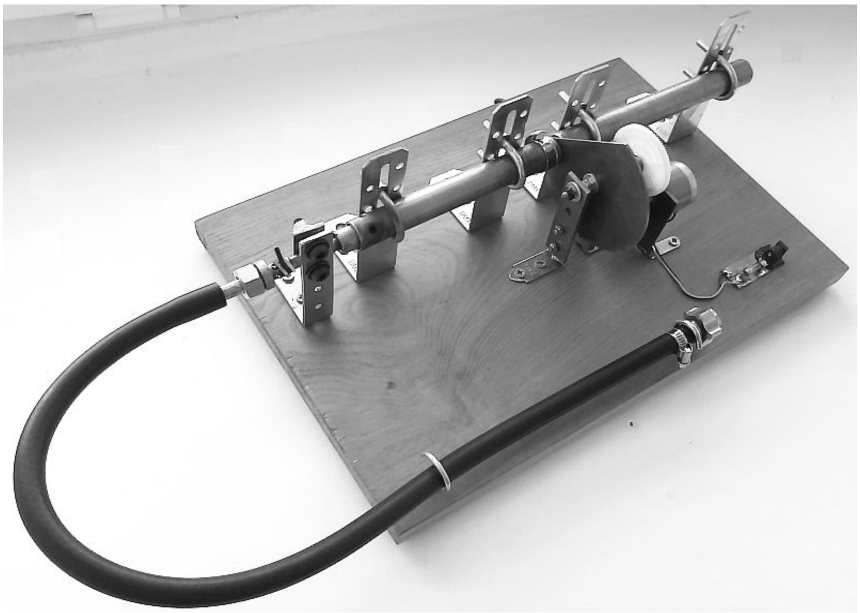


Fig. 6. Main view of the laboratory stand to research on dynamic properties of thermocouples

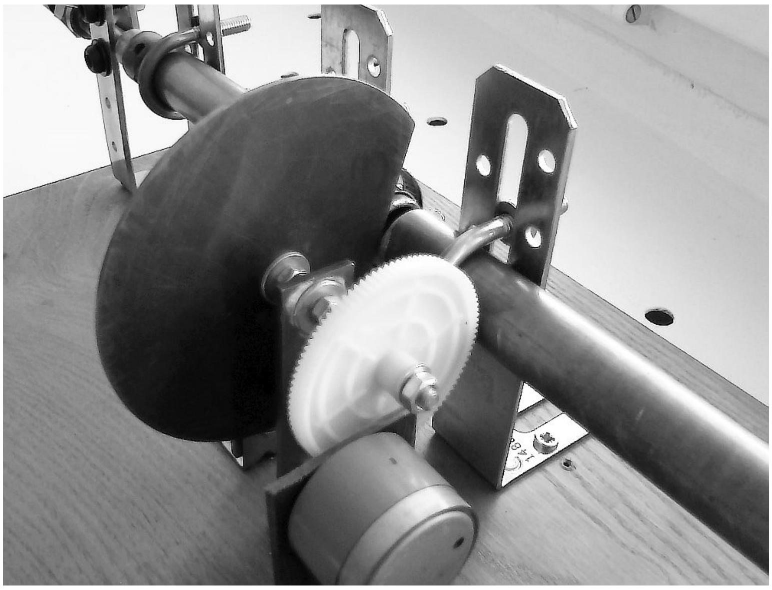


Fig. 7. Details of choking throttle

5. Results of numerical simulation of heat exchange between thermocouple and exhaust gas washing it.

Despite for supporting by the producers of time constant values for the thermocouples, it is not known for what conditions (ex. type, temperature, velocity of fluid washing the thermoelement etc.) or which method (analytical or experimental) were used to determine them. That is why before starting the experimental reserach on the laboratory stand, time constant values for the miniature thermocouples available in the offer of the Termo-Precyzja company were determined analytically. Calculations were made based on algorithm presented above, assuming specific conditions for the fluid flow in the gasodynamic process. Obtained results enabled to rationally choose the thermocouple to the measurements of high variable temperatures of hot air, being the gas analysed on the built research stand.

In order to determine the value of time constant for the considered thermocouple type, the following input data were assumed:

- fluid washing the thermocouple - air, for the pressure p=101,3 kPa;
- air velocity - 1,5 m/s;
- air temperature - 100^{o}C;
- material of thermocouple shield - stop inconell 600 (producer's data);
- electrodes material - 90% Ni, 10%Cr;
- insulation material - 97% MgO.

Dimensions of the elements, which thermocouple consists of, are also given (by the producer):

$l=2\cdot10^{-2}$ m – lenght of thermocouple
$d_{zew}=5\cdot10^{-4}$ m – outer diameter of the thermocouple sheath
$d_{wew}=3\cdot10^{-4}$ m – inner diameter of the thermocouple sheath
$d_t=9\cdot10^{-5}$ m – diameter of thermoelectrodes

It was assumed that the thermocouple is located at the flowing channel in a way that its axis is perpendicular to the direction of the flow of the air washing it. This assumption is relevant for determining the characteristic dimension ocurring in critical numbers for particular types of thermocouples.

After making calculations according to presented algorithm, the results were obtained and are presented in the table 1. To most important parameters characterising the thermocouple belong: characteristic dimension, Reynolds number, heat transfer coefficient and time constant providing the most crucial information: time of reaction of thermocouple for the given changes of air temperature.

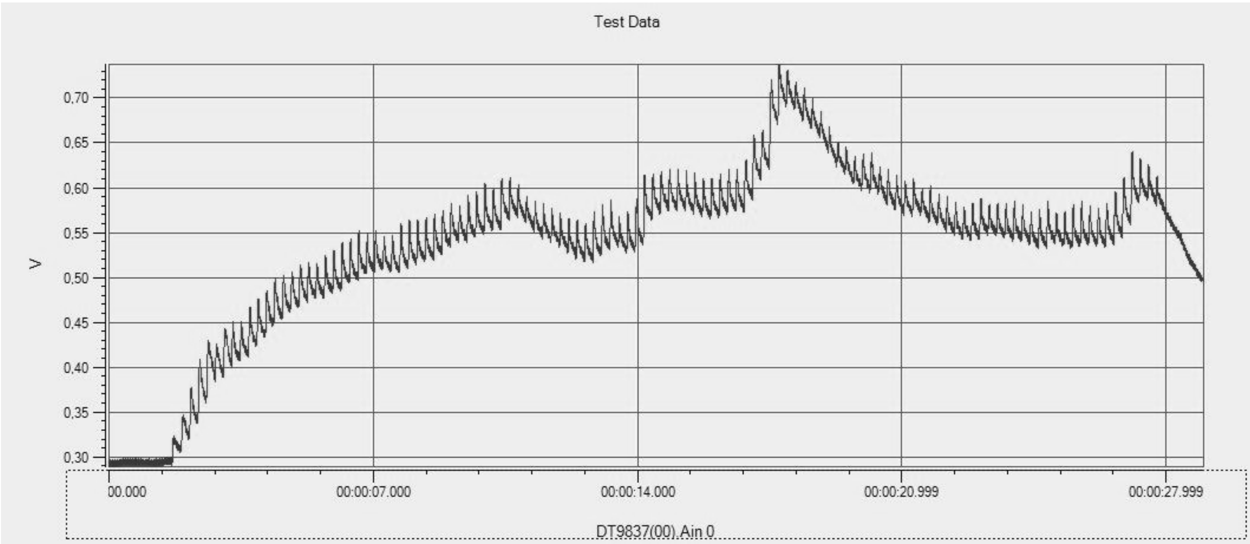
Tab. 1. Calculated values for the thermocouple at the outer diameter of $5\cdot10^{-4}$ m

Type of thermocouple	welded	open weld	insulated
Characteristic dimension d [m]	$75\cdot10^{-5}$	$13{,}5\cdot10^{-5}$	$75\cdot10^{-5}$
The outer diameter of sheath d_{zew} [m]	$5\cdot10^{-4}$	$5\cdot10^{-4}$	$5\cdot10^{-4}$
Reynolds number Re [-]	48,6	3,87	48,6
Heat transfer coefficient α [W/m^{2}K]	243,7	884,3	140,4
The time constant τ [s]	$322\cdot10^{-3}$	$98\cdot10^{-3}$	$1900\cdot10^{-3}$

From the calculations made, it follows that the best dynamic properties distinguish the thermocouples with open weld, but they also have the lowest durability in the assumed conditions of flow (high values of temperature and velocity of air flow). However, thermocouples with weld insulated from the sheath do not fulfill the requirements enabling to apply them in measurements of high variable temperatures, despite their highest durability. Therefore, the most appropriate solution seems to be the thermocouple with the weld welded to the sheath, which with good durability and corrosion properties is also characterised by satisfactory dynamic properties.

6. Results of emprical research on the built laboratory stand and their analysis.

After choosing the optimum construction solution of the thermocouple type K with the weld welded to the sheath, insulated internaly with MgO, the experiment was conducted on the stand to analyse dynamic properties of thermocouples and its results are presented in the pictures 8, 9 and 10.



Pic.. 8 Voltage corresponding with temperature during the entire experiment

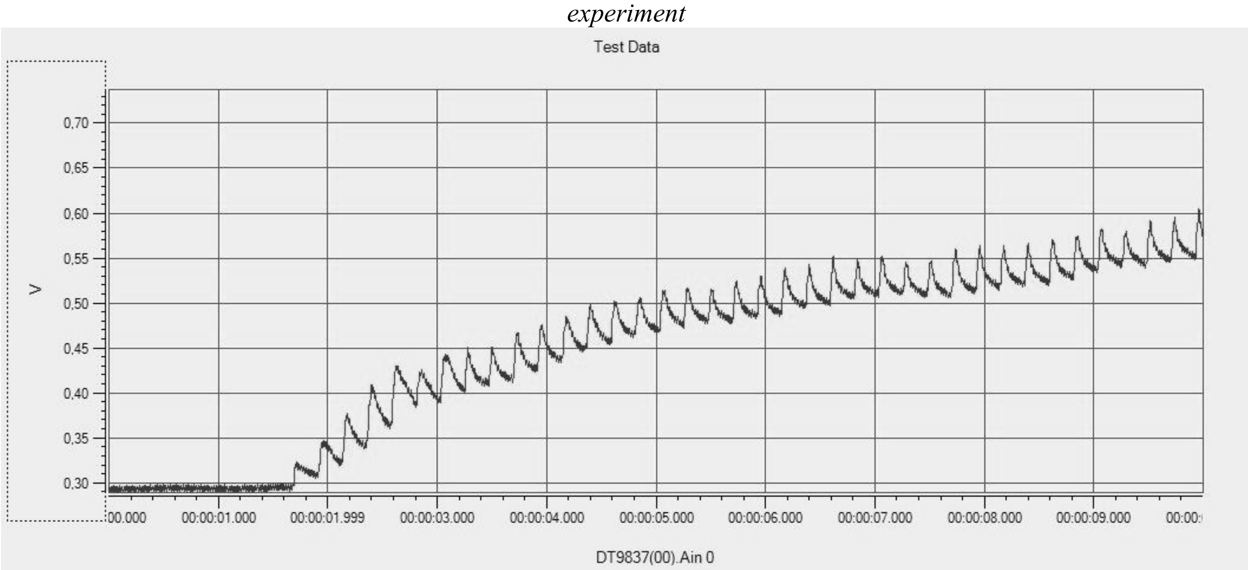


Fig. 9 Voltage corresponding with temperature during the initial phase of the experiment

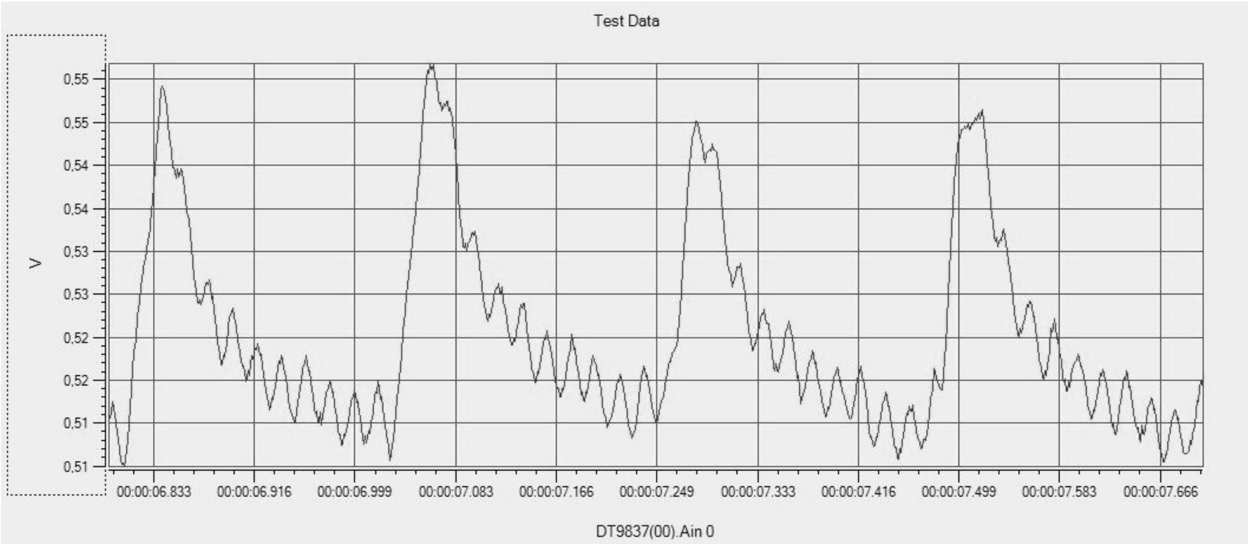


Fig. 10 Voltage corresponding with temperature in particular cycles

In the picture 8, the change in voltage was presented (corresponding with the temperature of the gas in the exhaust channel) during one cycle of the experiment. The noise induced by simulation of states of partial aptitude for work can be detected (macro scale), as well as signals induced by rotations of the choking throttle (micro scale). In the picture 9, initial phase of the experiment is presented, during which the temperature of the gas increased as the exhaust pipe heated up. Picture 10 however presents four randomly chosen cycles, each of them reflecting one impulse of the gas during opening of the exhaust pipe by the choking throtlle (simulation of the exhaust phase in the diesel engine with rotational velocity 480 rev/min).

7. Summary.

Temperature of the thermodynamic factor can enable to obtain diagnostic information, reffering to technical state of construction elements limiting the working space of piston machines. It is connected with the necessity of measurements of high variable temperatures of flowing gas, which are relevant issue in contemporary metrology. In order to elaborate a reliable methodology of diagnostic research, it is necessary to determine the shift of phase and amplitude of high variable temperature of gas obtained during empirical research with respect to its theoretical value. It will provide information crucial for further research on laboratory stand of piston machines (diesel engine and piston air compressor), as well as for improving stands and methodology of the research itself, aiming to minimalization of the impact of external factors on the results of the experiment. It will enable to elaborate the methodology for diagnosis of piston machines working space, based on the results of the measurements of high variable temperatures of exhaust gases and identification of well-known and identifiable damages of piston machines with limited control capacity.

References

[1] Korczewski Z., Puzdrowska P. „*Analytical method of determining dynamic properties of thermocouples used in measurements of quick – changing temperatures of exhaust gases in marine diesel engines*", Combustion Engines, nr 162 (3) (2015), s. 300-306;

[2] Korczewski Z., Zacharewicz M. „*Diagnostyka symulacyjna układu turbodoładowania okrętowego tłokowego silnika spalinowego*", Zeszyty naukowe Akademii Marynarki Wojennej nr 2 (169) 2007

[3] Puzdrowska P. "*Laboratory stand for investigations of the quick – changing temperature of gas flowing in the piston compressor outlet channel*", Journal of Polish CIMAC – vol. 9, nr 1 (2014), s. 111 – 119;

[4] Wiśniewski S.: *Pomiary temperatury w badaniach silników i urządzeń cieplnych*. WNT, Warszawa 1983;