Article citation info:
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*. 2015, **162**(3), 300-306. ISSN 2300-9896.

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PTNSS–2015–3342

Analytical method of determining dynamic properties of thermocouples used in measurements of quick – changing temperatures of exhaust gases in marine diesel engines

The article presents selected issues of mathematical modeling of heat exchange between the thermocouple and the exhaust gas flowing them, in unsteady conditions. On the way of energy balancing consideration of thermodynamic processes developed differential equations describing the dynamic properties for three versions of the design sheathed thermocouples: with weld isolated from the sheath, with weld welded the sheath and with the open weld. On this basis were determined the equations describing the time constants. After substituting the appropriate the input data: materials and heat-flow, provided by the manufacturer (the company "Termo-Precyzja") it was possible to compare the numerical values of the time constants of thermocouples and make a rational choice for the diagnostic tests conducted marine diesel engines.

Key words: *technical diagnostics, marine diesel engine, dynamic exhaust gas temperature measurements*

Analityczna metoda wyznaczania własności dynamicznych termopar stosowanych w pomiarach szybkozmiennej temperatury spalin wylotowych silnika okrętowego

W artykule przedstawiono wybrane zagadnienia modelowania matematycznego wymiany ciepła pomiędzy termoparą i omywających ją spalinami w warunkach nieustalonych. Na drodze bilansowania energii rozpatrywanych procesów termodynamicznych opracowano równania różniczkowe opisujące cechy dynamiczne trzech wersji konstrukcyjnych termopar płaszczowych: ze spoiną izolowaną od płaszcza, ze spoiną zgrzewaną do płaszcza i ze spoiną odkrytą. Na tej podstawie wyznaczono równania opisujące ich stałe czasowe. Po podstawieniu odpowiednich danych wejściowych: materiałowych i cieplno-przepływowych, udostępnionych przez producenta (firma „Termo-Precyzja") możliwe było porównanie wartości liczbowych stałych czasowych tych termopar i dokonanie racjonalnego doboru dla potrzeb prowadzonych badań diagnostycznych silników okrętowych.

Słowa kluczowe*: diagnostyka techniczna, okrętowy silnik tłokowy, dynamiczne pomiary temperatury spalin wylotowych*

1. Introduction

The starting point in designing the measuring and diagnostic system to analyse quick - changing the marine engine exhaust gas temperature is proper selecting the thermocouple and method of its installation in the flow channel. These decisions make the basis for developing a mathematical model of the structure of the thermocouple. Taking into account exhaust gas flow conditions enables to evaluate basic dynamic parameters of the thermocouple, which are the time constant and the attenuation coefficient. These values are needed to determine thermal inertia of the thermocouple to be used for measuring the periodically changing exhaust gas temperature. Evaluated is the response of the thermocouple (treated as a dynamic element with concentrated parameters) to sinusoidal exhaust gas temperature excitation, including the phase shift and the amplitude of changes of the temperature recorded by the thermocouple with respect to the excited real changes of the exhaust gas temperature [Korczewski].

Most producers offer three versions of sheathed thermocouples which differ by durability and the response delay time to the set fluid temperature excitation. 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.

2. Analytical model of thermocouple

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 of 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[1]. The thermometric (voltage) characteristic of the NiCr-Ni thermoelement is linear and sufficiently steep within the used measuring range [Wiśniewski, 1983].

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)[2]. 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.

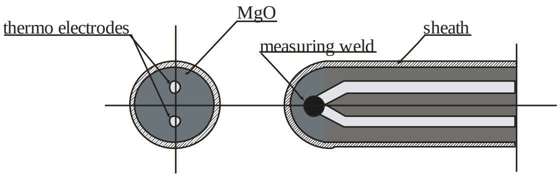

Fig. 1. Longitudinal and cross section of the final part of the sheathed thermocouple with the weld insulated from the sheath

To limit maximally the disturbances resulting from heat exchange by radiation between the thermocouple, exhaust gas, and flow channel walls, which may affect the performed dynamic measurements of unsteady exhaust gas temperature, the thermocouple should be installed in a cylindrical insulating shield (of 10 mm in diameter) which also stagnates the flowing exhaust gas. A standard thermocouple of the engine's measurement system is planned to be adopted for this purpose (Fig. 2).

On the other hand, to minimise the exhaust gas temperature measurement error resulting from the heat flow along the thermocouple sheath, the measuring length of the section *l* flowed around by the exhaust gas should be at least five times as long as the outer sheath diameter D_{zp}[3], and positioned in such a way that the inlet to the stagnating chamber of the shield is in the axis of the flow channel.

After assuming the simplest zero-dimensional model of the thermocouple and the plane temperature distribution in the sheath and thermo electrodes, and neglecting heat exchange by radiation[4] between the thermocouple, exhaust gas, and the insulating shield, the unsteady energy balance equations for the final segment of the thermocouple flowed around by the engine exhaust gas can be determined in the following way:

- change of the internal energy accumulated in the sheath and in the ceramic insulation material (MgO) is equal to the flux of heat transfer from the exhaust gas to walls and insulation:

$$\frac{dU_p}{d\tau} = A_{zp} \cdot \alpha_{wp} \cdot \left(T_{sp} + r \cdot \frac{c^2}{2 \cdot c_{psp}} - T_p \right) \quad (1)$$

- change of the internal energy accumulated in the thermo electrodes is equal to the flux of heat conducted through the sheath and the ceramic insulation material (MgO):

$$\frac{dU_{te}}{d\tau} = A_{te} \cdot \frac{1}{R_{\lambda p}} \cdot \left(T_p - T_{te} \right) \quad (2)$$

where:

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,
T_{sp} – temperature of the exhaust gas,
T_p – temperature of the sheath,
T_{te} – temperature of the thermo electrodes,
c – averaged velocity of the exhaust gas flow in the channel,
r – temperature recovery coefficient (for the stagnating chamber situated perpendicularly to the exhaust gas flow direction – values ranging between 0,90 and 0,96[5] are assumed [Wiśniewski, 1983]),

[1] The corrosion resistance of the Inconel alloy at the presence of CO_2 and SO_2 in the exhaust gas at temperatures exceeding 800 K is much weaker.

[2] The sheathed thermocouple with open weld reveals best dynamic characteristics, which are accompanied, however, by the lowest durability, especially when working in the exhaust gas flow (the time counted in minutes). That is why this type of thermocouple is not used in diagnostic practice.

[3] The longer the measuring segment of the thermocouple flowed around by the exhaust gas of the temperature equal to the measured temperature, the larger the isothermal area around the thermocouple and the smaller the effect of the heat flow along the sheath on the measurement result.

[4] It was assumed that the exhaust gas does not absorb and does not emit radiation, while the emissivity of the polished thermocouple sheath made of the alloy Inconell 600 and that of the insulating shield covered with silver are negligibly small ($i_{ncon-ell}$=0,11-0,16, ε_{Ag}=0,03-0,05).

[5] The temperature recovery coefficient for turbulent flow is also determined from the formula which

c_{psp} – averaged specific heat of the exhaust gas at constant pressure,

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:

$$R_{\lambda p} = \frac{s}{\lambda_p} \tag{3}$$

λ_p – averaged heat transfer coefficient of the constructional material of the sheath and insulation,

s – thickness of the sheath and insulation.

After expanding and relevant transformations, a system of ordinary differential equations of the first order was obtained which describes the heat transfer process in the thermocouple during the unsteady exhaust gas flow:

$$\frac{dT_p}{d\tau} = \frac{A_{zp} \cdot \alpha_{wp} \cdot \left(T_{sp} + r \cdot \frac{c^2}{2 \cdot c_{psp}} - T_p \right)}{C_{pi}} \tag{4}$$

$$\frac{dT_{te}}{d\tau} = \frac{A_{te} \cdot \frac{1}{R_{\lambda p}} \cdot \left(T_p - T_{te} \right)}{C_{te}} \tag{5}$$

where:

C_{pi} – total thermal capacity of the constructional material of the sheath and insulation:

$$C_{pi} = m_{Inconel} \cdot c_{Inconel} + m_{MgO} \cdot c_{MgO} \tag{6}$$

C_{te} – total thermal capacity of the constructional material of the thermo electrodes:

$$C_{te} = m_{NiCr} \cdot c_{NiCr} + m_{Ni} \cdot c_{Ni} \tag{7}$$

After determining the averaged temperature of the sheath and the insulating material from Equation (5) we get:

$$T_p = \frac{C_{te} \cdot \frac{dT_{te}}{d\tau}}{A_{te} \cdot \frac{1}{R_{\lambda p}}} + T_{te} \tag{8}$$

and after two-sided differentiation:

$$\frac{dT_p}{d\tau} = \frac{C_{te}}{A_{te} \cdot \frac{1}{R_{\lambda p}}} \cdot \frac{d^2 T_{te}}{d\tau^2} + \frac{dT_{te}}{d\tau} \tag{9}$$

Placing formulas (8) and (9) into Equation (4) we arrive at the final form of the equation describing the dynamics of the analysed type of thermocouple[6]:

$$T_{sp} = -r \cdot \frac{c^2}{2 \cdot c_{psp}} + T_{te} + \left(\frac{C_{pi}}{A_{zp} \cdot \alpha_{wp}} + \frac{C_{te}}{A_{te} \cdot \frac{1}{R_{\lambda p}}} \right) \cdot \frac{dT_{te}}{d\tau} + \frac{C_{pi}}{A_{zp} \cdot \alpha_{wp}} \cdot \frac{C_{te}}{A_{te} \cdot \frac{1}{R_{\lambda p}}} \cdot \frac{d^2 T_{te}}{d\tau^2} \tag{10}$$

The form of Equation (10) reveals that the thermocouple with the weld insulated from the sheath is the second order inertial term, and its time constant is described by the equation:

$$\tau_{cz} = \sqrt{\frac{C_{pi}}{A_{zp} \cdot \alpha_{wp}} \cdot \frac{C_{te}}{A_{te} \cdot \frac{1}{R_{\lambda p}}}} \tag{11}$$

When analysing dynamic properties of the thermocouple with the weld welded to the sheath (Fig. 2), an assumption is to be made that the weld measures the temperature T_k of the sheath end.

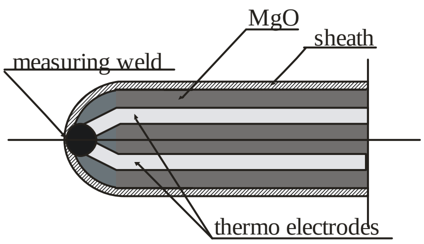

Fig. 2. Longitudinal section of the final part of the sheathed thermocouple with the weld welded to the sheath

Like in the previous case, assuming additionally that the heat transfer between the sheath and the exhaust gas takes only place by convection, and that the temperature at each point of the measuring segment of the sheath (a dynamic element with concentrated parameters) is constant and equal to

makes use of the Prandtl number: $r = \sqrt[3]{\Pr}$. For r=1 the measured exhaust gas temperature corresponds to the stagnation temperature.

[6] Constant values in the equation, which characterise the constructional structure of the thermocouple, can be determined from characteristic dimensions of the sheath and thermo electrodes, taking also into account the density, specific heat, and heat transfer coefficient of the used materials. At the same time in engineering calculations, the thermal transmittance is assumed as a constant which only depends on the velocity and temperature of the flowing exhaust gas.

the temperature of the weld, this type of thermocouple can be modelled as the dynamic element of the first order described by the following balance equation:

$$\frac{dU_k}{d\tau} = A_{zp} \cdot \alpha_{wp} \cdot \left(T_{sp} + r \cdot \frac{c^2}{2 \cdot c_{psp}} - T_k \right) \quad (12)$$

Relevant transformations lead to the following form of the thermocouple dynamics equation:

$$T_{sp} = \frac{C_p}{A_{zp} \cdot \alpha_{wp}} \cdot \frac{dT_k}{d\tau} + T_k \quad (13)$$

This time the time constant is described by the formula:

$$\tau_{cz} = \frac{C_p}{A_{zp} \cdot \alpha_{wp}} \quad (14)$$

where:
C_p – thermal capacity of the constructional material of the sheath:

$$C_p = m_{Inconel} \cdot c_{Inconel} \quad (15)$$

Comparing Equations (11) and (14) reveals that the time constant of the thermocouple with the weld welded to the sheath is smaller than that of the thermocouple with the weld insulated from the sheath, and the difference is the total thermal capacity of thermo electrodes and the insulating material related to relevant heat transfer surfaces. We should keep in mind, however, that this approach is substantial simplification, as in practice, the thermo electrodes are to be added to the weld in calculations, which would lead to slight increase of the thermocouple's time constant. Nevertheless, the value which is much more difficult to assess analytically is the increase of the time constant due to heat transfer from the measuring weld via thermo electrodes to the insulating material, the more so that at the same time the heat is delivered to the thermo electrodes through the sheath and the insulating material.

The shortest time of thermocouple response to the set exhaust gas temperature excitation can be obtained using the sheathed structure with open weld – Fig. 3.

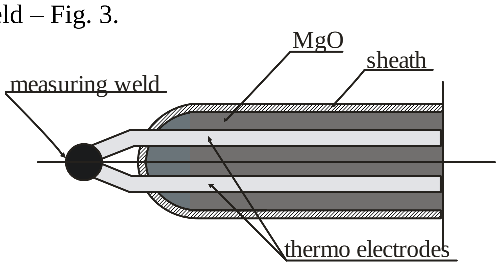

Fig. 3. Longitudinal section of the final segment of the sheathed thermocouple with open weld

From the point of view of unsteady process modelling, the measuring weld can be considered a dynamic element with concentrated parameters. Assuming that the weld has the shape of a sphere and all its surface is involved in convection heat transfer (only) from the exhaust gas flowing around it[7], its dynamic characteristic can be described by the following balance equation:

$$\frac{dU_s}{d\tau} = A_s \cdot \alpha_{ws} \cdot \left(T_{sp} + r \cdot \frac{c^2}{2 \cdot c_{psp}} - T_s \right) \quad (16)$$

which after expanding takes the following form:

$$T_{sp} = \frac{C_s}{A_s \cdot \alpha_{ws}} \cdot \frac{dT_s}{d\tau} + T_s \quad (17)$$

where:
A_s –surface of the measuring weld,
T_{sp} – temperature of the exhaust gas,
T_s – temperature of the measuring weld,
α_{ws} – thermal transmittance between the exhaust gas and the measuring weld.

The time constant of the thermocouple is given by the formula:

$$\tau_{cz} = \frac{C_s}{A_s \cdot \alpha_{ws}} \quad (18)$$

When calculating the thermal capacity C_s of the measuring weld, we should take into account that, due to technological reasons, its diameter is up to twice as large as that of the welded thermo electrodes:

$$C_s = m_s \cdot c_s \quad (19)$$

The most difficult task in the presented procedure is to determine analytically the thermal transmittance in formulas (11), (14) and (18). It is a function of many variables, including: the velocity and nature of the exhaust gas flow which define the thickness of thermal boundary layer, and thermophysical properties of the exhaust gas with a given chemical composition (viscosity, density, specific heat, and heat transfer coefficient) as temperature functions.

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

[7] In fact, like for the sheathed thermocouple with the weld welded to the sheath, thermal consequences of the presence of electrodes near the weld to the time constant are to be additionally taken into account.

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:

$$\alpha = Nu \cdot \frac{\lambda_{sp}}{d} \quad (20)$$

where:

λ_{sp} – thermal conductivity of the exhaust gas at given temperature,

d – characteristic linear dimension, for instance the measuring weld diameter[8],

Nu – Nusselt number, characterising the relation between the heat transfer intensity and the temperature field in the boundary layer of the exhaust gas flow:

$$Nu = f(\mathrm{Re}, \mathrm{Pr}) \quad (21)$$

where:

$\mathrm{Re} = \dfrac{d \cdot c \cdot \rho_{sp}}{\eta_{sp}}$ – Reynolds number,

$\mathrm{Pr} = \dfrac{\eta_{sp} \cdot c_{psp}}{\lambda_{sp}}$ – Prandtl number.

c – velocity of the exhaust gas flow,

ρ_{sp} – density of the exhaust gas,

η_{sp} – dynamic viscosity of the exhaust gas.

A form of the function defining the Nusselt number is to be decided upon after experimental investigations performed for a given case of turbulent flow. For instance, the Nusselt number for the flow around a spherical measuring weld of the thermocouple can be determined from the formula worked out by Frössling [Furmański and Domański, 2004]:

$$Nu = 2 + 0{,}6 \cdot \mathrm{Re}^{1/2} \cdot \mathrm{Pr}^{1/3} \quad (22)$$

This way, the methodology to determine the thermal transmittance is reduced to determining the Reynolds and Prandtl numbers, and calculating the Nusselt number from the criterial equation (22). The obtained results make the basis for calculating α from a properly transformed function being a definition of *Nu* (20).

[8] Nusselt, Reynolds and Grashof numbers include a characteristic linear dimension, which is to be qualitatively the same for similar systems, i.e. understood in the same way by the author and the user of the criterion equation. In this situation, a parameter bearing the name of so-called equivalent diameter d_e, is frequently used. For the thermocouple having a cylindrical shape it can be determined as the ratio of the volume V to the surface A of the sphere having the same volume as the thermocouple flowed around by the exhaust gas: d_e=6V/A. For the sheathed thermocouple with open spherical measuring weld of the diameter d: d_e=d.

3. Results of accounts and analysis

Despite sharing the manufacturers data of thermocouples time constants, it is not known to what conditions (eg. type, temperature and velocity of the fluid flowing over the thermocouple etc.) and what method (analytical or experimental) they have been appointed. Therefore, before proceeding to the engine the experimental studies were determined by an analysis of miniature thermocouples' time constants offered by "Termo–Precyzja" company [www.termo-precyzja.com.pl]. Calculations were based on the algorithm proposed above, assuming specific conditions of fluid flow in the testing gas dynamics processes. Obtained results allowed making a rational choice of a thermocouple intended for the measurements of quick-changing temperatures of the marine engine's exhaust gases.

In order to determine time constants for the considered types of thermocouples the following input data were assumed:

- the fluid flowing around the thermocouple - exhaust gas with the chemical composition: 13% CO_2, 11% H_2O, 76% N_2, for a pressure p = 101,3 kPa;
- exhaust gas velocity - 50 m/s;
- exhaust gas temperature – 773 K;
- thermocouple sheath material - an alloy inconell 600 (manufacturer data);
- thermoelectrodes material - 90% Ni, 10% Cr;
- insulating material - 97% MgO.

There are also known (specified by the manufacturer) dimensions of the elements that make the thermocouple structure:

1) *for thermocouple Ø $5\cdot10^{-4}$ m:*
   - $l=2\cdot10^{-2}$ m – thermocouple's length,
   - $d_{zew}=5\cdot10^{-4}$ m - outside diameter of the thermocouple sheath,
   - $d_{wew}=3\cdot10^{-4}$ m - internal diameter of the thermocouple sheath,
   - $d_t=9\cdot10^{-5}$ m - thermoelectrode's diameter.
2) *for thermocouple Ø $25\cdot10^{-5}$ m:*
   - $l=2\cdot10^{-2}$ m – thermocouple's length,
   - $d_{zew} = 25\cdot10^{-5}$ m - outside diameter of the thermocouple sheath,
   - $d_{wew} = 2\cdot10^{-4}$ m - internal diameter of the thermocouple sheath,
   - $d_t = 25\cdot10^{-6}$ m – thermoelectrode's diameter.

It was assumed that the thermocouple is positioned in the flow channel in such a way that its axis is perpendicular to the direction of the exhaust gas flow. This assumption is important while determining the characteristic dimension occurring in the criterial numbers for different types of thermocouples.

After the calculation carried out according to the algorithm presented above the results were gathered in Table 1 (for the thermocouple at the outside diameter of 0,5 mm) and Table 2 (for the thermocouple at the outside diameter of 0,25 mm). The most important parameters characterizing the thermocouple are, as follows: characteristic dimension, the Reynolds number, heat transfer coefficient and time constant. They allows getting the most important information: the thermocouple response time to alterations within the exhaust gas temperature.

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

Type of thermocouple	welded	open weld	insulated
Characteristic dimension d [m]	$75\cdot10^{-5}$	$11{,}25\cdot10^{-5}$	$75\cdot10^{-5}$
The outer diameter of sheath d_{zew} [m]	$5\cdot10^{-4}$	$5\cdot10^{-4}$	$5\cdot10^{-4}$
Reynolds number Re [-]	492,46	73,87	492,46
Heat transfer coefficient α [W/m²K]	1170,74	3736,28	519,72
The time constant τ [s]	$67{,}02\cdot10^{-3}$	$19{,}31\cdot10^{-3}$	$987{,}3\cdot10^{-3}$

Table. 2. Calculated values for the thermocouple at the outside diameter of $25\cdot10^{-5}$ m

Type of thermocouple	welded	open weld	insulated
Characteristic dimension d [m]	$37{,}5\cdot10^{-5}$	$31{,}25\cdot10^{-6}$	$37{,}5\cdot10^{-5}$
The outer diameter of sheath d_{zew} [m]	$25\cdot10^{-5}$	$25\cdot10^{-5}$	$25\cdot10^{-5}$
Reynolds number Re [-]	246,23	20,52	246,23
Heat transfer coefficient α [W/m²K]	1757,99	9071,72	713,05
The time constant τ [s]	$5{,}58\cdot10^{-3}$	$2{,}21\cdot10^{-3}$	$208{,}6\cdot10^{-3}$

The performed calculations demonstrated that thermocouples with the open weld have got the best dynamic characteristics, but they also have got the lowest stability established flow conditions (high temperatures and flow rate of the exhaust gases). On the other hand thermocouples with the weld insulated from the sheath do not meet the requirements of allowing their usage for measurements of quick-changing temperatures, despite the highest durability. Therefore, the most appropriate solution seems to be the thermocouple with the weld welded to the sheath, which has got good mechanical and corrosion properties and is also characterized with satisfactory dynamic features.

4. Final remarks and conclusions

Dynamic exhaust gas temperature measurements in selected control sections of the manifold supplying the turbocompressor enable to calculate the enthalpy flux of successive pressure pulses of the exhaust gas leaving engine cylinders. Its value, averaged over one operating cycle, brings important diagnostic information on the technical state of cylinder workspaces, and of the injection at charge cycle systems. To make this information available, we should work out the technology of measurement and mathematical processing of the recorded quick - changing exhaust gas temperature signal, which will enable to reproduce truly its real time-history as the function of engine crankshaft revolution angle. Through the drawn up mathematical model was possible to determine on the analytical way the time constants, which in turn allowed the assessment of the dynamic properties of the available versions of thermocouples. Rationally selected thermocouple with the weld welded to the sheath, reconciling the dynamic and strength properties, for diagnostic tests planned for marine engines. Research of this type is planned to be performed in real operating conditions on a marine four-stroke engine Sulzer type A, using an ultra-miniature thermocouple made of a material revealing very good conductivity and minimal thermal inertia. This thermocouple will be mounted in a properly modified sheath used by a standard thermocouple. The measuring procedure will base on the method first used by Prof. Stanisław Rutkowski to examine a laboratory engine in 1976. It is also planned to develop a method to verify the analytical model drawn up on the basis of the thermocouple simultaneous measurements of quick-changing pressures and temperatures of compressed air in the outlet channel of two-stage piston compressor Espholin H3S.

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