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EXHAUST GAS TEMPERATURE MEASUREMENTS IN DIAGNOSTICS OF TURBOCHARGED MARINE INTERNAL COMBUSTION ENGINES PART II DYNAMIC MEASUREMENTS

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ABSTRACT

The second part of the article describes the technology of marine engine diagnostics making use of dynamic measurements of the exhaust gas temperature. Little-known achievements of Prof. S. Rutkowski of the Naval College in Gdynia (now: Polish Naval Academy) in this area are presented. A novel approach is proposed which consists in the use of the measured exhaust gas temperature dynamics for qualitative and quantitative assessment of the enthalpy flux of successive pressure pulses of the exhaust gas supplying the marine engine turbocompressor. General design assumptions are presented for the measuring and diagnostic system which makes use of a sheathed thermocouple installed in the engine exhaust gas manifold. The corrected thermal inertia of the thermocouple enables to reproduce a real time-history of exhaust gas temperature changes.

Keywords: diagnostic, internal combustion engine, exhaust gas temperature

INTRODUCTION

Analysing temperature and pressure changes of the exhaust gas leaving the cylinders of a turbocharged marine engine within one operating cycle provides opportunities for direct qualitative and quantitative assessment of the enthalpy flux of successive pressure pulses of the exhaust gas supplying the turbocompressor. Its value, expressed in J/ OWK deg within one operating cycle for a single-cylinder four-stroke engine (each cycle corresponds to two crankshaft revolutions), is calculated by integrating the exhaust gas enthalpy flux formula within the endpoints defined by crankshaft rotation angles:

$$\overline{\dot{H}}_{imp(OWK)} = \int_{0}^{720} \dot{m}_{sp} \cdot c_{sp}\left(T_{sp}\right) \cdot T_{sp}\ d\alpha_{OWK} \tag{1}$$

In case of a multi-cylinder engine in which the collecting manifold (or manifolds) supplying the turbocompressor has a number of individual exit passages from particular cylinders connected to it, the enthalpy flux is to be integrated within precisely defined endpoints (240 OWK degrees for a four-stroke engine) which result from: (1) the operating sequence of the cylinders, (2) the opening and closing angles of the exhaust valves in particular cylinders, (α_{OWK}OZW) and (α_{OWK}ZZW) respectively, and (3) the angles of overlapping of successive exhaust gas flow pulses (α_{OWK}N):

$$\overline{\dot{H}}_{imp(OWK)} = \int_{\alpha_{OWK}\ OZW}^{\alpha_{OWK}\ (ZZW-N)} \dot{m}_{sp} \cdot c_{sp}\left(T_{sp}\right) \cdot T_{sp}\ d\alpha_{OWK} \tag{2}$$

To express in J/s the enthalpy flux of the pressure pulses of the exhaust gas supplying the turbocompressor within one engine operation cycle, the result of integration of Eq. (1) or

(2) is to be multiplied by a conversion ratio which converts the crankshaft revolution angles to a corresponding time expressed in seconds:

$$\overline{\dot{H}}_{imp(sek)} = \frac{n}{60 \cdot 360} \cdot \overline{\dot{H}}_{imp(OWK)} \qquad (3)$$

MEASURING HIGH-SPEED EXHAUST GAS TEMPERATURE CHANGES

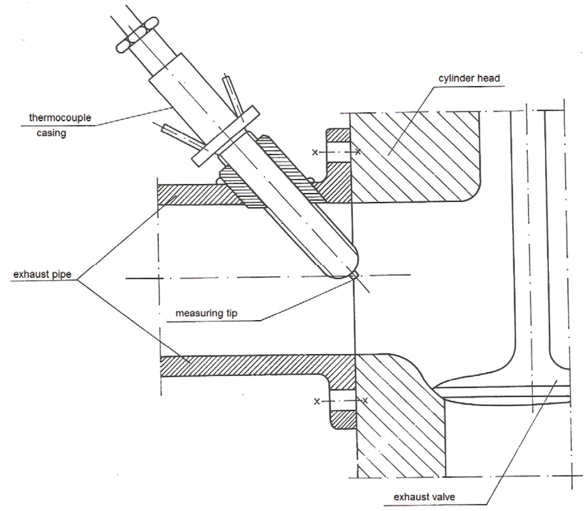
In the adopted research method a key metrological issue is to calculate the average time-histories of high-speed changes of the exhaust gas temperature in a selected control cross section of the turbocompressor inlet channel[1]. This requirement results from the fact that successive individual time-histories are deformed, as a consequence of errors in the exhaust gas temperature and pressure measurements, and disturbances, mainly connected with: non-repeatability of the fuel combustion process in successive cylinders, fluctuations of the rotational speed of the crankshaft, wave phenomena in the flow channels (reflection, resonance and/or interference of waves), operation of the engine rotational speed controller, etc., [Korczewski, 2003].

In order to reproduce reliable time-histories, factors which cause their deformation are to be minimised by approximating the measured results in the crankshaft revolution angle domain. Many methods to approximate the measured high-speed variables are available [Polanowski and Zellma, 1997, Polanowski, 2007]. A method which is very simple and simultaneously reveals satisfying accuracy from the point of view of the diagnostic purpose of the analysis is the so-called method of synchronous averaging, described by [Korczewski, 2008, Korczewski and Zacharewicz, 2012]. This approximation method has been already used to measure high-speed air and exhaust gas pressures in flow channels of marine engines.

Another metrological issue of high importance is to secure the required resolution of the exhaust gas temperature measurement, at least of the order of 0,1 OWK degree (3600 measuring points per one crankshaft revolution), which in case of marine engines with the rotational speed of up to 1000 rpm requires the use of recorders with minimal sampling frequency of 60 kHz. 8,33 operating cycles are executed during one second of four-stroke engine operation, which means that one operating cycle lasts 0,12 second and the above mentioned recorder will be able to record 7200 measuring samples per one operating cycle. This sampling frequency is believed to allow the time-history of exhaust gas temperature changes to be reliably reproduced. At the same time, taking into account that signal recoding for synchronous averaging purposes should last at least 16 operating cycles, which corresponds to 32 crankshaft revolutions in the four-stroke engine (and 16 revolutions in the two-stroke engine), all this will result in writing 230.400 bytes to the memory of a single-channel recorder with 12-bit measuring card. At present, A/D converter cards with those parameters are easily available on electronic market.

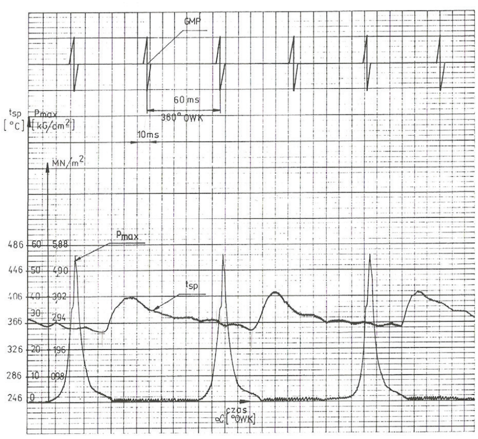
When designing an effective diagnostic system for a marine engine working in real operating conditions at the assumption that this system bases on high-speed temperature measurements[2], the essential metrological problem is the selection and installation of thermocouples in the turbocompressor inlet channel. First attempts in this area were made in Poland by Prof. Stanisław Rutkowski of the Naval College in Gdynia (now: Polish Naval Academy) in the 1970s [Rutkowski, 1976]. Having a measuring system at his disposal which was considered very advanced for those years, he managed to record time-histories of exhaust gas temperature changes in a laboratory single-cylinder four-stroke Diesel engine. The temperature was measured directly behind the exhaust valve (Fig. 1), on the background of the developed indicator graph – Fig. 2.

Fig. 1. Thermocouple installation place in the exhaust gas exit channel



[Rutkowski, 1976]

a)



[1] The methodology to calculate instantaneous mass flow rates of the exhaust gas supplying the turbocompressor, based on dynamic measurements of the stagnation pressure and static pressure recorded in two control cross sections of the exhaust gas exit channels, has been described in detail by [Korczewski, 2003] and is not discussed here.

[2] Performed on the engine installed in the ship engine room.

b)

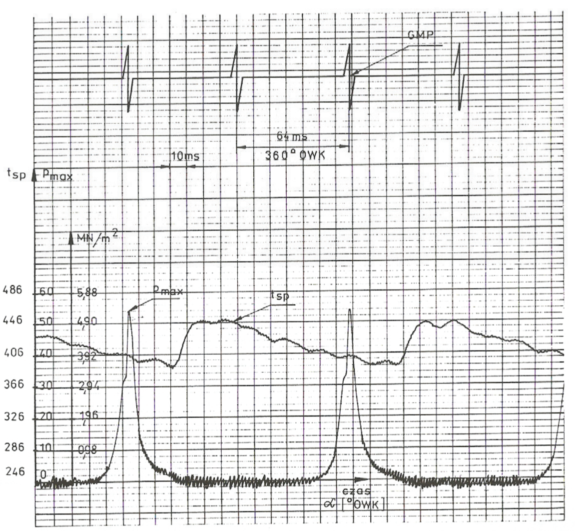


Fig. 2. Time-histories of changes of: exhaust gas temperature, cylinder pressure, and GMP piston position vs. crankshaft rotation angle in single-cylinder four-stroke Diesel engine in two different technical states [Rutkowski, 1976]: a)reference state – full technical ability, b) state of partial technical ability – after introducing engine combustion chamber leakiness (compression pressure decreased from 3,53 to 3,13 MPa).

The research aimed at determining diagnostic relations between the cylinder compression pressure drop and the dynamics of changes of the recorded exhaust gas temperature. Based on the performed calculations, the following dynamic properties of the recorded signal were determined:

- maximal amplitude of instantaneous values of the exhaust gas temperature,
- rate of temperature increase and decrease,
- engine crankshaft rotation angle at which the maximal temperature is recorded.

Dynamic changes of the exhaust gas temperature were measured using a specialised[3] ultra-miniature CrNiTi thermocouple having thermo electrode wires of 0,15 mm in diameter. The thermocouple was installed in the sheath of 6 mm in diameter and cooled in the water flow of precisely defined flow rate (min. 15 dm^3/min) to prevent the water from boiling. During the measurements the open weld of the thermocouple protruded by about 1,5 mm from the sheath. The apparatus bearing the name of the loop recorder, made by the Austrian company Honeywell, was used to amplify and record the signal generated by the thermocouple.

The comparison analysis of the numerical data characterising the recorded high-speed time-histories of exhaust gas temperature and pressure in the engine cylinder clearly indicate obvious thermodynamic consequences of partial loss of combustion chamber tightness: the decrease of the compression pressure results in: (1) the increase of the maximal amplitude of the instantaneous temperature values of successive exhaust gas flux pulses, (2) higher intensity of temperature decreases and increases, and (3) the decrease of the OWK angle at which the temperature maximum is recorded.

Theoretically, the recorded time-histories of the exhaust gas temperature changes could be used for formulating more in-depth diagnostic conclusions oriented on assessing energy consequences of the combustion chamber leakiness. Unfortunately, this turned out impossible due to limitations imposed by the analogue nature of operation of the measuring apparatuses used for measurements:

- loop recorder – the loop as the elements which records high-speed changes of thermoelectric voltage, reveals certain mechanical inertia which precludes its reliable on-line reproduction. At the same time, after developing the photo-sensitive paper of the loop recorder, the only possibility of quantitative comparison analysis of the recorded exhaust gas flux temperature and pressure pulses consisted in their manual planimetring.
- water cooled thermocouples – leaving aside the threat of possible sheath tightness loss and the resultant water flow into the engine workspace, the open weld of the thermoelement is exposed to the action of the high temperature exhaust gas in direct vicinity of the exhaust valve. This high temperature provokes intensive oxidation and diffusion processes, which change the chemical composition and crystalline structure of the thermocouples, with all further consequences for the recorded thermoelectric voltage, and the durability and reliability of the thermocouple.

The above arguments, supported by new possibilities introduced by dynamically developing numerical measurement systems and computer tools of numerical processing of the recorded measurement data, and by personal metrological experience gained by the author during many years of diagnostic examination of thermal and flow systems of internal combustion engines, were the reason why a decision was made to improve remarkably the technology of exhaust gas temperature measurements in Diesel engines, in order to allow it to be used for evaluating the technical state of real objects – engines installed in ship engine rooms.

EVALUATING DYNAMIC PROPERTIES OF THE THERMOCOUPLE

The starting point in designing the measuring and diagnostic system to analyse high-speed changes of the marine engine exhaust gas temperature is proper selection of the place for installing thermocouples. Obviously, the lower the top value of the interval of variations of the measured exhaust gas temperature, the longer the durability and reliability of the used thermocouple. Consequently, the most appropriate place for installing thermocouples seem to be the exhaust manifold region situated directly at turbocompressor inlet, i.e. the place where thermocouples for standard exhaust gas temperature measurements are installed (see Fig. 5 in Part I of the article). Also other arguments, such as good accessibility and serviceability of the engine element which enables easy preservation of its undisturbed functioning, speak in favour of

[3] The thermocouples were made to measure dynamically the temperature of powder gases in cannons.

this selection. Indeed, exhaust gas flux pulses in this manifold region are much weaker than at cylinder exits, but the basic diagnostic goal here is limited to determining the enthalpy flux of successive pressure pulses of the exhaust gas supplying the turbocompressor in the same fixed control cross section of the manifold.

The next stage in designing the measuring system is 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 *Tspp* recorded by the thermocouple with respect to the excited real changes of the exhaust gas temperature *Tsprz* – Fig. 3.

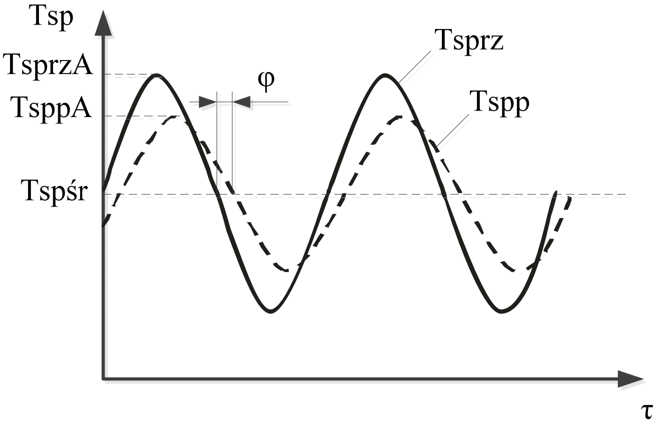


Fig. 3. Thermocouple response to sinusoidal exhaust gas temperature excitation

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 Inconel, 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 gas4. 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. 4), (2) the weld welded to the sheath (Fig. 5), and (3) the open weld (Fig. 6)5. 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 high-speed engine exhaust gas temperature measurements should be determined analytically.

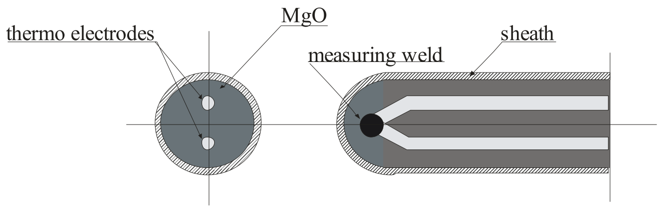


Fig. 4. Longitudinal and cross section of the final part of the sheathed thermocouple with the weld insulated from the sheath

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. 5).

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}[6], 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[7] between the thermocouple, exhaust gas, and the

[4] 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.

[5] 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.

[6] 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.

[7] It was assumed that the exhaust gas does not absorb and does not emit radiation, while the emissivity of the polished thermocouple sheath made

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:

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

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

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

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[8] are assumed [Wiśniewski, 1983]),
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:

$$R_{\lambda p} = \frac{s}{\lambda_p} \quad (6)$$

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

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:

$$\frac{dT_p}{d\tau} = \frac{A_{zp} \cdot \alpha_{wp} \cdot \left(T_{sp} + r \cdot \frac{c^2}{2 \cdot c_{psp}} - T_p \right)}{C_{pi}} \quad (7)$$

$$\frac{dT_{te}}{d\tau} = \frac{A_{te} \cdot \frac{1}{R_{\lambda p}} \cdot \left(T_p - T_{te} \right)}{C_{te}} \quad (8)$$

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

$$C_{pi} = m_{Inconel} \cdot c_{Inconel} + m_{MgO} \cdot c_{MgO} \quad (9)$$

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

$$C_{te} = m_{NiCr} \cdot c_{NiCr} + m_{Ni} \cdot c_{Ni} \quad (10)$$

After determining the averaged temperature of the sheath and the insulating material from Equation (8) we get:

$$T_p = \frac{C_{te} \cdot \frac{dT_{te}}{d\tau}}{A_{te} \cdot \frac{1}{R_{\lambda p}}} + T_{te} \quad (11)$$

and after two-sided differentiation:

$$\frac{dT_p}{d\tau} = \frac{C_{te}}{A_{te} \cdot \frac{1}{R_{\lambda p}}} \cdot \frac{d^2 T_{te}}{d\tau^2} + \frac{dT_{te}}{d\tau} \quad (12)$$

Placing formulas (11) and (12) into Equation (7) we arrive at the final form of the equation describing the dynamics of the analysed type of thermocouple[9]:

$$T_{sp} = -r \cdot \frac{c^2}{2 \cdot c_{psp}} + T_{te} + \left(\frac{C_{pi}}{A_{zp} \cdot \alpha_{wp}} + \frac{C_{te}}{A_{te} \cdot \frac{1}{R_{\lambda p}}} \right) \cdot \frac{dT_{te}}{d\tau} + \\ + \frac{C_{pi}}{A_{zp} \cdot \alpha_{wp}} \cdot \frac{C_{te}}{A_{te} \cdot \frac{1}{R_{\lambda p}}} \cdot \frac{d^2 T_{te}}{d\tau^2} \quad (13)$$

The form of Equation (13) 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:

of the alloy Inconel 600 and that of the insulating shield covered with silver are negligibly small ($\varepsilon_{Inconel}$=0,11-0,16, ε_{Ag}=0,03-0,05).

[8] The temperature recovery coefficient for turbulent flow is also determined from the formula which makes use of the Prandtl number: $r = \sqrt[3]{\Pr}$. For r=1 the measured exhaust gas temperature corresponds to the stagnation temperature.

[9] 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.

$$\tau_{cz} = \sqrt{\frac{C_{pi}}{A_{zp} \cdot \alpha_{wp}} \cdot \frac{C_{te}}{A_{te} \cdot \frac{1}{R_{\lambda p}}}} \tag{14}$$

When analysing dynamic properties of the thermocouple with the weld welded to the sheath (Fig. 5), an assumption is to be made that the weld measures the temperature T_k of the sheath end

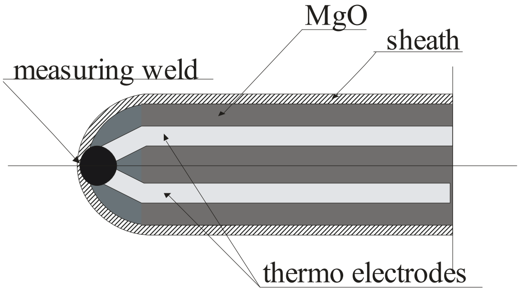


Fig. 5. Longitudinal section of the final part of the sheathed thermocouple with the weld welded to the sheath

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 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:

$$\frac{dU_k}{d\tau} = A_{zp} \cdot \alpha_{wp} \cdot \left(T_{sp} + r \cdot \frac{c^2}{2 \cdot c_{psp}} - T_k \right) \tag{15}$$

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

$$T_{sp} = \frac{C_p}{A_{zp} \cdot \alpha_{wp}} \cdot \frac{dT_k}{d\tau} + T_k \tag{16}$$

This time the time constant is described by the formula:

$$\tau_{cz} = \frac{C_p}{A_{zp} \cdot \alpha_{wp}} \tag{17}$$

where:

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

$$C_p = m_{Inconel} \cdot c_{Inconel} \tag{18}$$

Comparing Equations (14) and (17) 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. 6

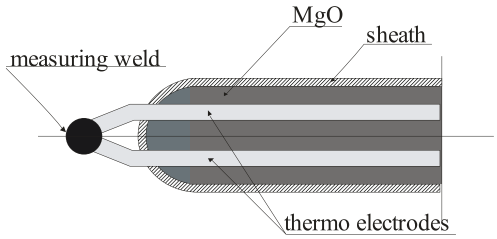


Fig. 6. Longitudinal section of the final segment of the sheathed thermocouple with open weld.

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[10], its dynamic characteristic can be described by the following balance equation:

$$\frac{dU_s}{d\tau} = A_s \cdot \alpha_{ws} \cdot \left(T_{sp} + r \cdot \frac{c^2}{2 \cdot c_{psp}} - T_s \right) \tag{19}$$

which after expanding takes the following form :

$$T_{sp} = \frac{C_s}{A_s \cdot \alpha_{ws}} \cdot \frac{dT_s}{d\tau} + T_{sk} \tag{20}$$

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

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

$$\tau_{cz} = \frac{C_s}{A_s \cdot \alpha_{ws}} \tag{21}$$

When calculating the thermal capacity C_s of the measuring

[10] 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.

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:

$$C_s = m_s \cdot c_s \quad (22)$$

The most difficult task in the presented procedure is to determine analytically the thermal transmittance in formulas (14), (17) and (21). 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 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:

$$\alpha = Nu \cdot \frac{\lambda_{sp}}{d} \quad (23)$$

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

d – characteristic linear dimension, for instance the measuring weld diameter[11],

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

$$Nu = f(\mathrm{Re}, \mathrm{Pr}) \quad (24)$$

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

$\mathrm{Pr} = \frac{\eta_{sp} \cdot c_{psp}}{\lambda_{sp}}$ – 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]:

$$Nu = 2 + 0{,}6 \cdot \mathrm{Re}^{1/2} \cdot \mathrm{Pr}^{1/3} \quad (25)$$

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 (25). The obtained results make the basis for calculating α from a properly transformed function being a definition of Nu (23).

An aspect which also should be taken into account when analysing the dynamics of high-speed engine exhaust gas temperature measurements is the inertia of the entire data transmission system, including the converter, measuring card, recorder, etc. However, based on the requirement of simultaneous measurements of the exhaust gas pressure and temperature in the flow channel to calculate the enthalpy flux of the exhaust gas supplying the turbocompressor we can assume that this inertia is negligibly small.

Consequently, using the calculating formulas given in [Wiśniewski, 1983] we can calculate the phase shift of changes of the temperature recorded by the thermocouple with respect to real temperature changes in the exhaust gas:

$$\varphi = -arctg\,\varpi \cdot \tau_{cz} \quad (26)$$

where: ϖ – frequency of temperature change pulsations.

The real amplitude of exhaust gas temperature changes can also be determined as:

$$T_{sprzA} = T_{sppA} \cdot \sqrt{1 + \varpi^2 \cdot \tau^2} \quad (27)$$

As a result, a real time-history of changes of high-speed engine exhaust gas temperature can be reproduced based on properly recalculated temperature values recorded by the thermocouple:

$$T_{sprz} = T_{spsr} + T_{sppA} \cdot \sin(\varpi \cdot t - arctg\,\varpi \cdot \tau) \quad (28)$$

A sine qua non condition for using the above formulas to assess dynamic characteristics of the thermocouple is sufficient regularity of exhaust gas temperature changes within one engine operation cycle. Otherwise, two thermocouples of identical thermophysical characteristics but of different diameters are to be used for measurements, according to the methodology proposed for the first time by H. Pfriem in 1936. Unfortunately, in the next 80 years this methodology was not used in practice for diagnostic examination of workspaces of internal combustion engines.

[11] 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.

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 an charge cycle systems. To make this information available, we should work out the technology of measurement and mathematical processing of the recorded high-speed exhaust gas temperature signal, which will enable to reproduce truly its real time-history as the function of engine crankshaft revolution angle. 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.

BIBLIOGRAPHY

1. Buczek A., Nocoń J., Słupek S.: Thermo technology (in Polish). AGH, Kraków, 2002.
2. Furmański P., Domański R.: Hest transfer (in Polish). Oficyna Wydawnicza Politechniki Warszawskiej, Warszawa, 2004.
3. Jaremkiewicz M., Taler D. Sobota T.: Measuring transient temperature of the medium in power engineering machines and installations. Elsevier. Applied Thermal Engineering. 29 (2009), 3374 – 3379.
4. Korczewski Z.: Method to diagnose turbocharged marine engines based on results of examination of gas dynamics processes in the exhaust gas system (in Polish). Diagnostyka, Vol. 28/2003 r., p. 87-95
5. Korczewski et al.: Method to diagnose warship engines with limited ability for intra-cylinder pressure measurements based on results of examination of gas dynamics processes in the turbo-charging system (in Polish). Research project No. 0T00B02129 financed by MNiSW. AMW Gdynia, 2008.
6. Korczewski Z.: An entropy function application within the selection process of diagnostic parameters of marine diesel and gas turbine engines. Polish Maritime Research, 2(65)/2010, Vol.17, p. 29-35.
7. Korczewski Z.: Exhaust gas temperature measurements in diagnostic examination of naval gas turbine engines. Part III. Diagnostic and operating tolerances. Polish Maritime Research, No. 4(71)/2011, Vol.18, p. 49-53.
8. Korczewski Z.: Analysing possible use of the diagnostic model of piston-crankshaft systems in internal combustion engines and evaluating its practical applicability for controlling rationally the operation of these engines taking into account an expert system (in Polish). Publication within the framework of the research project Nr N509 494638 financed by MNiSW. Gdansk University of Technology, 2012.
9. Korczewski Z., Zacharewicz M.: Alternative diagnostic method applied on marine diesel engines having limited monitoring susceptibility. Transactions of the Institute of Measurement and Control, Great Britain SAGE - Vol. 34, No. 8/December/2012, 2012, p. 937-946.
10. Kluj S.: Diagnostics of marine machinery (in Polish). Monographic publication. AM Gdynia 2000.
11. Pfriem, H.: Zur messung vernderlicher temperaturen von gasen und flssigkeiten (On the measurement of fluctuating temperatures of gases and fluids). Forschung auf dem Gebiete des Ingenieurwesens,7(2)/1936, pp. 85-92 (in German).
12. Piotrowski I., Witkowski K.: Operation of marine internal combustion engines (in Polish). Monographic publication. Gdynia Maritime University, Gdynia 2002.
13. Polanowski S., Zellma M.: The peak value determination of cylinder pressure rate with the basic splines or follow-up approximation. Journal of KONES'97, s. 297-303, 1997.
14. Polanowski S.: A study of methods to analyse indicator diagrams in the aspect of marine engine diagnostics (in Polish) . Zeszyty Naukowe AMW, nr 169A. Gdynia 2007.
15. Rutkowski S.: Using dynamic exhaust gas temperature measurements in diagnostics of marine internal combustion engines (in Polish). A copy of a typed abstract of the article written in 1976.
16. Rychter T., Teodorczyk A.: Theory of piston engines (in Polish). WKiŁ, Warsaw 2006.
17. Scott W.: Diagnosing Causes of High EGT in Marine Engines. Marine Machinery, Engines & Controls. Edited by Lamar Stonecypher (updated: 11/2/2011).
18. Wisłocki K.: Charging systems for high-speed internal combustion engines (in Polish). WKiŁ, Warszawa 1991.
19. Wiśniewski S.: Technical thermodynamics (in Polish). WNT, Warszawa 2005.

20. Wiśniewski S.: Temperature measurements in examination of engines and thermal facilities (in Polish). WNT, Warszawa 1983.

21. Woodyard D.: Pounders marine diesel engines and gas turbine. Great Britain ELSEVIER, 2004 (eighth edition).

22. Wojnowski W.: Marine internal combustion engine power plants. Part I (in Polish). Polish Naval Academy. Gdynia 1998.

23. www.intercars.com.pl

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