Gradient heat flux measurement as monitoring method for the diesel engine

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Abstract. The usage of gradient heat flux measurement for monitoring of heat flux on combustion chamber surface and optimization of diesel work process is proposed. Heterogeneous gradient heat flux sensors can be used at various regimes for an appreciable length of time. Fuel injection timing is set by the position of the maximum point on the angular heat flux diagram however, the value itself of the heat flux may not be considered. The development of such an approach can be productive for remote monitoring of work process in the cylinders of high-power marine engines.

1. Introduction
The understanding of the heat transfer in the combustion chamber is key in improving engine efficiency. The rapid changes in gas temperature, pressure and velocity field contribute to its complexity resulting in a highly transient and spatial nature of the heat flux.

Heat transfer measurements inside the combustion chamber pose a challenge in instrumentation due to the harsh environment. In this work Heterogeneous Gradient Heat Flux Sensors (HGHFS) are implemented at different locations in the combustion chamber. The spatially measured heat flux database is a valuable contribution to existing literature.

The first experiments of heat flux measurement by HGHFS carried out in 1996 [1], were of a pioneer nature, but of little practical importance: sensors based on bismuth are inoperable above 200...250 °C.

The principle of HGHFS work is based on transversal Seebeck effect. HGHFS allow direct measurement of heat flux with extraordinary response time of $10^{-8}...10^{-9}$ s. Heat flux is determined as follows:

$$q = \frac{e}{S_0 F}$$  \hspace{1cm} (1)

where $q$ is heat flux (W/m²), $e$ is signal of HGHFS (mV), $S_0$ is sensitivity of sensor (mV/W), $F$ is area of sensor (m²).
2. Experimental setup

2.1. Apparatus

The research was conducted on Indenor XL4D, four-cylinder, four-stroke, water cooled, divided chamber, medium-high speed diesel engine of automobile duty. The engine has total displacement volume of 1.357 cm$^3$, a cylinder bore of 78 mm, a piston stroke of 71 mm, a compression ratio of 23, maximal power of 35 kW at 5000 revolutions per minute (rpm), maximal torque of 84.3 N·m at 2500 rpm.

Figure 1 shows the draw of the measurement system. The first piece is optical top dead center (TDC) marker. The marker outputs square pulse with a dip during peak phase in order to achieve the precise detection of TDC.

The second piece are heat flux sensors made of nickel-steel composition. Such composition allows to use HGHFS in aggressive ambient of combustion chamber for a long time. Sensors have dimensions of $4 \times 4 \times 0.2$ mm. Thus size of sensors allows to consider HGHFS do not distort temperature field [1].

The data registration was performed by National Instruments measurement complex. The virtual instrument was built in LabVIEW. For measuring PXI-6289 multifunction module via terminal block TB-2706 was used. Signals were recorded with the resolution of 1° of crankshaft angle.

![Figure 1. Measurement system diagram.](image1)

2.2. Calibration of heat flux sensor

HGHFS must be calibrated before measurement. For this purpose, the calibration system was built. Figure 2a shows the schematics of the calibration test cell. The calibration was realised according to the Joule heating at different temperatures. In this case, an axial electric heater in a cylindrical tube generates Joule heat flux, and the HGHFS fixes the heat flux. Figure 2b shows typical calibration curve for HGHFS based on nickel-steel composition. The relative uncertainty was 7.6%.
2.3. Installation of sensors
Pilot series of experiments were conducted with HGHFS installed on the cylinder head’s wall by probe. Figure 3 shows the schematics of probe and installation of single HGHFS. Sensor was mounted flush with surface of cylinder head.

In the second stage of research four HGHFS’ were mounted on cylinder head wall as it is shown on figure 4. Wire assemblies were lead out through the service opening used in the first part of the experiment.

Figure 2. Schematics of calibration system (a) and sensitivity versus sensor temperature (b).
3. Results

In this work instantaneous heat flux was measured for two different regimes: motored and fire operation. The engine speed was 1500 rpm. The measurements were conducted with no load.

Figure 5 shows experimental diagrams for pressure, temperature and instantaneous heat flux, concerning motored operation. It can be seen that the maximum of heat flux is near “hot” TDC [2] and occurs earlier than maximum of wall temperature. One can observe that closing of inlet valve near 180° before TDC and opening of exhaust valve near 180° after TDC affect the instantaneous heat flux. In the first case heat flux sharply decrease. In the second one it can be noted moderate increasing.

Figure 6 shows corresponding changes of instantaneous heat flux and advance injection angle (AIA). It can be observed that deviation from default injection angle leads to reducing of heat flux value. Also maximum of heat flux drifts further from TDC. Decrease of injection angle by 18° leads to shifting of heat flux maximum by 60° and reducing its value by 20%.

During operation with late injection angle it can be seen sharp fall of heat flux near TDC. It is caused by heat consumption of fuel for evaporation.
Figure 6. Variation of instantaneous heat flux at different advance injection angle.

Figure 7a shows the instantaneous heat flux into each measuring point for motored operation at 1500 rpm. It can be seen that maximum of heat flux is achieved simultaneously. The difference of maximum values is explained by diversity of velocity on the cylinder head’s wall. It can be noted a fluctuation during gas exchange stroke. It is caused by active mixing of gas in course of this stroke.

Figure 7b shows the instantaneous heat flux into each measuring point for fired operation at 1500 rpm. It can be seen that maximum of heat flux is achieved simultaneously as in motored operation. Heat flux are more sharp here, and their values increase.

4. Conclusions
In this work a new instrument of measuring heat flux was implemented. Results show stable work of HGHFS for a long period of time. Our results correspond with data from other researchers [3,4].

Timing and value of maximum of instantaneous heat flux are tightly linked with advance injection angle. On the regimes with late injection angle it is observed injection process.

HGHFS measure instantaneous heat flux directly. This approach allows to monitor heat flux in the combustion chamber for optimising the working process by varying advance injection angle.
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