Research of heat transfer in combustion chamber of diesel engine on idle by gradient heat flux measurement method

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Abstract. Heat transfer research is one of key topics for internal combustion engine development. However, heat transfer study is a challenging task due to high value and rapid change in temperature and heat flux inside the combustion chamber. In this paper, experimental study is presented with implementation of heterogeneous gradient heat flux sensors. Heat flux was measured by a probe and at several points of a firedeck. Heat fraction to a firedeck was calculated at various engine speeds. The heat transfer coefficient at investigated points is calculated. Comparison with other studies is provided.

1. Introduction
Understanding of heat transfer in a combustion chamber of internal combustion engine (ICE) is a critical part of engine development. For many years thermometry was the only method for measuring the heat flux in a combustion chamber of ICE. The temperature difference between the junctions of thermocouples varies from fractions to units of centigrade [2]. Such small amplitude and high rate of temperature during operation imposes strong requirements to the measuring equipment. The manufacture of high-acting thermocouples is challenging [3]. Also it is necessary to determine accurately the coordinates of junctions and control one-dimensionality of the heat flux during measurements [4]. To recalculate the heat flux, an artificial technique of estimating the “zero line” is used [5].

In this work a new way of heat flux measurement in the combustion chamber of ICE is proposed. This new method uses heterogeneous gradient heat flux sensors (HGHFSs). The principle of HGHFS work is based on the transversal Seebeck effect. The heterogeneous gradient heat flux sensors allow direct measurement of heat flux with extraordinary response time of $10^{-8} \ldots 10^{-9}$ s. The heat flux is determined as follows:

$$q = \frac{e}{S_0 F}$$

where $q$ stands for heat flux per unit area (W/m$^2$), $e$ stands for signal of HGHFS (mV), $S_0$ stands for volt-watt sensitivity of HGHFS (mV/W), $F$ stands for area of HGHFS (m$^2$).

2. Measurement facility
2.1. Apparatus
The study was conducted on Indenor XL4D, four-cylinder, four-stroke, water cooled, divided chamber, medium-high-speed diesel engine of automobile duty. The engine has a total displacement
volume of 1.357 cm³, a cylinder bore of 78 mm, a piston stroke of 71 mm, a compression ratio of 23, maximum power of 35 kW at 5000 revolutions per minute (rpm), and maximum torque of 84.3 N·m at 2500 rpm.

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

The second piece includes heat flux sensors made of nickel-steel composite. Such material allows the use of HGHFS in aggressive ambient of the combustion chamber for a long time. All HGHFSs have dimensions of 4×4×0.2 mm.

The data registration was performed by the National Instruments measurement complex. The virtual instrument was coded in LabVIEW. The PXI-6289 multifunction module via terminal block TB-2706 was used for measurements. Signals were recorded with resolution of 0.16° of crankshaft rotation angle (CRA).

2.2. Mounting of sensors
First series of experiments were conducted with HGHFS installed into the cylinder head wall by the probe. Figure 2 shows the schematics of the probe and installation of single HGHFS (it was mounted flush with the surface of the cylinder head).
At the second stage of research, four HGHFSs were mounted on the cylinder head inner wall (Figure 3). Wires were lead out through the service opening used in the first part of the experiment. Near each HGHFS, two K-type thermocouples at a time were installed to calculate the heat transfer coefficient.

![Figure 3. Installation of HGHFSs on the firedeck.](image)

3. Results

Instantaneous heat flux vs CRA was obtained on idle for the engine speed from 600 to 1900 rpm in an increment of 100 rpm. Only few regimes are shown in Figure 4. As it was assumed the heat flux increases with engine speed rising.

![Figure 4. Instantaneous heat flux at various engine speeds.](image)

We calculated the share of heat through the firedeck and the heat carried away in the cooling system normalized to supplied heat. Figure 5 shows distribution of heat at various engine speeds. The heat flux carried away by the cooling system decreases with engine speed rising. On the contrary, the heat flux carried away through the firedeck to the cooling system (which is a part of the heat flux going to the cooling system) rises with engine speed increasing. It can be explained by reducing time for heat transfer. Results are corresponding with other researches [5 et al.].
In the range of engine speed from 1300 to 1700 rpm oscillations of great amplitude are observed. It may be caused by the choice of regime: fluctuation of fuel supply may be up to 50\% respectively to injection rate on idle. The uncertainty of heat flux measurement is no more than 5.1\%.

![Figure 5](image)

**Figure 5.** Heat carried away through firedeck and by cooling water.

Figure 6 shows instantaneous heat flux and heat transfer coefficient at various points of firedeck for the engine speed of 1500 rpm. The heat transfer coefficient was calculated according to the measured heat flux and temperature difference between wall and gas. At all points the heat flux remains positive, maximum occurs simultaneously for all cases. The maximum heat flux value is reached on HGHFS 2. Such a big difference of the values of instantaneous heat flux at various points can be explained by uneven distribution of fuel in the combustion chamber.

![Figure 6](image)

**Figure 6.** Instantaneous heat flux and heat transfer coefficient at various points of firedeck.

The maximum value of heat transfer coefficient is reached on HGHFS 4 and 2. Contrary to the heat flux curves, a big difference in position of maximums of heat transfer coefficients is observed.
Maximum is reached at 20° for HGHFS 1 and 3, and at 7° for HGHFS 2. For HGHFS 4, the maximum of heat transfer coefficient is found at 7° before TDC. We assume that while the maximum of heat flux is observed synchronically the time is needed for the heat flux to affect the gas motion.

Figure 7 shows the comparison with results of other researches. The study of the motored regime at 1500 rpm is in good agreement with results of [6] and [7]. A little difference in results is due to position of investigated points of firedeck.

![Figure 7. Validation of measurements for motored operation.](image)

We also compared our results for fired operation. The heat flux was measured at 1500 rpm. Figure 8 shows that our results are lower than in [6-10]. All compared studies were conducted for the load of 10 % and higher and it means bigger amount of injected fuel. Minor inequality of heat flux maximum timing comes from different fuel injection timing.

![Figure 8. Validation of measurements for fired operation.](image)
4. Conclusion
We have demonstrated a new solution for instantaneous heat flux measurement in the combustion chamber of a diesel engine: heterogeneous gradient heat flux sensors. The heterogeneous gradient heat flux sensors are robust and reduction of signal is easier in comparison with the known methods described in [6 – 10].

Our work revealed the significant difference in heat distribution of combustion chamber components at various regimes of engine operation. We believe this result will aid the researchers to improve understanding of thermal fatigue of the engine parts.

Our results correspond with data of other researches and can be useful at confirmation of heat transfer models.

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