

DETERMINATION OF A HEAT TRANSFER BETWEEN INJECTED DIESEL FUEL AND A TEMPERATURE CONTROLLED WALL

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Abstract

The paper presents results of the experimental determination of heat fluxes between diesel fuel jet and a steel wall. The experiments were performed in the high pressure and temperature rig at the Chalmers University. The experimental stand allowed setting the pressures and the temperatures in the chamber similar to the conditions in a diesel engine during the compression stroke. A standard common rail injecting system and an injector with a single hole nozzle were used. The measurements were taken for different pressures/temperature combinations. However, in respect to have similar jet formation conditions and fuel droplets penetration range, the air density in the chamber was kept on constant level.

The temperature-controlled wall was mounted perpendicular to the fuel jet. The wall was equipped with coaxial thermocouples for recording the surface temperatures. The thermocouples had very thin vacuum deposited junctions that offered very fast response. The recorded time histories of the surface temperatures were used to calculate the local heat fluxes on a basis of the one-dimensional transient heat conduction model.

The experimental chamber had an optical access allowing observing the jet and the swirl formation when the fuel reached the wall. A high-speed camera was used to record the jet behaviour.

Keywords: *heat transfer, spray-wall interaction, diesel fuel injection*

1. INTRODUCTION

Spray-wall interaction in direct injected diesel engines has been studied in many aspects. It has been found that for early injections, when pressure and temperature in a cylinder is relatively low, the fuel can reach the piston top due to long spray penetration [4]. In such situations the heat release rate can be influenced [5].

The spray-wall interaction can also affect soot formation and NO_x emissions [6]. The spray impinging the wall surface disturbs the evaporation process leading to insufficient combustion. Osuka et al. [7] studied this problem during cold start.

In all above cases the heat transfer between spray and wall seems to have big importance especially for secondary penetration parallel to the wall. Experimentally determined heat fluxes when the jet impinges the wall can be used to improve numerical models of spray-wall interaction.

2. EXPERIMENTAL STAND

Experiments were performed on a special test stand built at Department of Applied Mechanics at the Chalmers University. The main part of the stand is high temperature and high pressure chamber (Fig. 1). It consisted of two cylindrical steel shells with quartz windows for an optical access. The outer shell was thick to withstand pressure and the inner cylinder formed the injection chamber. The diesel fuel injector was axially mounted on the top wall. Below, perpendicularly to the fuel jet, round steel wall was placed. The wall temperature was controlled by an electric heater and a cooler. Depending on desired conditions water or air was used as a cooling medium.

The wall was equipped with coaxial surface thermocouples of type E. The thermocouple diameter was very small (~ 0.4 mm) to minimize deformation of the temperature field by the thermocouples. The sensing junction was made by coating the thermocouple tip by $0.5 \mu\text{m}$ layer of chromium. This ensured a very short response time of order of $3 \mu\text{s}$. The thermocouples were fixed in the wall with temperature resistive glue.

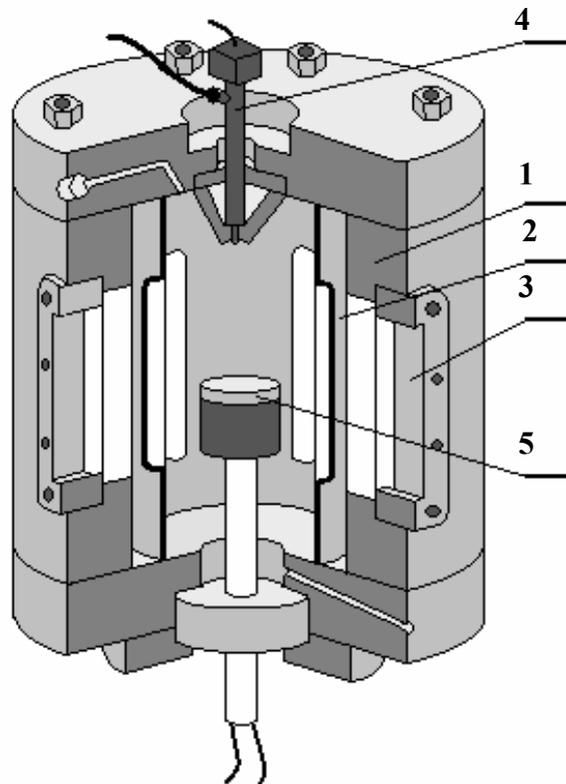


Fig. 1. Schematic drawing of the spray chamber; 1 – outer shell, 2 – inner cylinder, 3 – quartz window, 4 – injector, 5 – temperature controlled wall with thermocouples

A high pressure Bosch common-rail injector with a single hole nozzle with a diameter of 0.15 mm was used. The pump could deliver fuel with a pressure up to 135 MPa. The fuel pressure and injection timing were controlled electronically and could be set for up to three consecutive injections.

The test stand was equipped with a multi channel data acquisition system with a sampling rate up to 1.25 MHz. Images of fuel sprays were obtained by a high speed digital camera (Phantom v7.1) with a recording speed of up to $50,000$ frames per second at a resolution of 128×128 pixels.

3. HEAT FLUX DETERMINATION

One of the methods for determination of heat flux on the wall surface relies on the recording of this surface temperature. Variable heat flux acting upon the element being investigated causes changes in the temperature field inside the body according to the theory of unsteady heat conduction. Due to heat capacity of the wall material, temperature changes decrease with the body penetration. For quickly changing heat flux, the penetration depth is small and the heat transfer in a wall of sufficient thickness may be considered as one-dimensional unsteady heat conduction in a flat semi-infinite body [2]. This problem is described by the equation:

$$\frac{\partial T}{\partial x} = a \frac{\partial^2 T}{\partial x^2}, \quad (1)$$

with the unsteady boundary conditions:

$$\begin{aligned} \text{at } x \geq 0 \text{ and } t = 0 & \quad T = T_0 \\ \text{at } x = 0 \text{ and } t > 0 & \quad T = T_0(t), \end{aligned} \quad (2)$$

where:

T – temperature,
 t – time,
 x – dimensional variable,
 a – thermal diffusivity.

The exact solution for the problem has been given by Carslaw & Jaeger [1]. If $T(t)$ is a time function of a wall surface temperature then the instantaneous heat transfer density can be expressed as:

$$q(t_n) = \sqrt{\frac{k\rho c}{\pi}} \int_0^{t_n} \frac{1}{\sqrt{t-\tau}} \frac{dT}{d\tau} d\tau, \quad (3)$$

where:

k – heat conductivity,
 ρ – density,
 c – specific heat
 τ – integrating variable.

In the experiments the surface temperatures were collected by a data acquisition system as a series of discrete values at regular time intervals $\Delta\tau$. Approximating the time derivative of temperature by a differential quotient $\Delta T_i/\Delta\tau$ enabled to expand the integral into sum of integrals over single time steps. Solving the integrals led to the formula for numerical calculation of a local heat transfer rate:

$$q(t_n) = 2\sqrt{\frac{k\rho c}{\pi\Delta\tau}} \sum_{i=1}^n (T_i - T_{i-1}) (\sqrt{n-i+1} - \sqrt{n-i}), \quad (4)$$

where:

i, n – numbers of time steps.

The time interval $\Delta\tau$ should be sufficiently short to provide accurate approximation.

The installation of a thermocouple in a surface exchanging heat disturbs the temperature field inside a wall. The effect of this disturbance is the least when heat properties of the wall and thermocouple materials are similar. This condition is difficult to fulfil since the thermocouple is made of different materials. For the thermocouple of type E the best choice for a wall material is carbon steel or stainless steel because their properties are very similar to the one of the thermocouple material. Numerical simulations showed that for above combinations the error of heat flux measurements is less than 7% [3]. The error can be even lower if there is a thin layer of thermal insulation between the thermocouple and the wall limiting heat conduction in the radial direction.

4. RESULTS

In the chapter the selected results are presented to show how big differences in the heat flux can be achieved depending on the conditions. In all cases the standard diesel fuel was used and the injection pressure was set to 135 MPa. In the experiments the injection timing was set for two consecutive injections, each of duration 1000 μs , with the dwell time of 500 μs between them. The fuel temperature was kept constant at approximately 25°C by cooling the injector with cold water flowing close to the nozzle.

The wall with thermocouples was placed in the constant distance of 32 mm downstream the nozzle. The surface temperature was measured in two points: 1 – laying on the jet axis, 2 – in the distance of 6 mm from the axis. All other experiment conditions are collected in Tab. 1 together with peak values of heat flux reached for the all cases. Positive values of a heat flux meant the wall was heated, negative – the wall was cooled.

Tab. 1. Measurement conditions and peak heat fluxes

	P_{air} [bar]	T_{air} [°C]	T_{wall} [°C]	Peak heat flux [kW/m ²]	
				at point 1	at point 2
Case #1	27	150	60	980	1180
Case #2	27	150	170	-970	-380
Case #3	29	340	100	2150	2900
Case #4	29	340	180	800	1380
Case #5	47	450	120	350/-30	210/-240
Case #6	47	450	290	0	0

As one can see from the Tab. 1 the heat transfer between the impinging spray and the wall depends very much on the conditions. It can be very intensive and can change the direction. The peak values for heat flux were as high as almost 3 MW/m² for heating the wall (case #3) and to 1 MW/m² for cooling (case #2). But in certain conditions the heat transfer had no place at all (case #6). Fig. 2 shows detailed time histories of heat fluxes for the all cases. Each graph was

constructed on the basis of averaged surface temperatures for 10 consecutive measurements. That was necessary to eliminate electromagnetic noise caused by the injector drive and the fuel pressure controller.

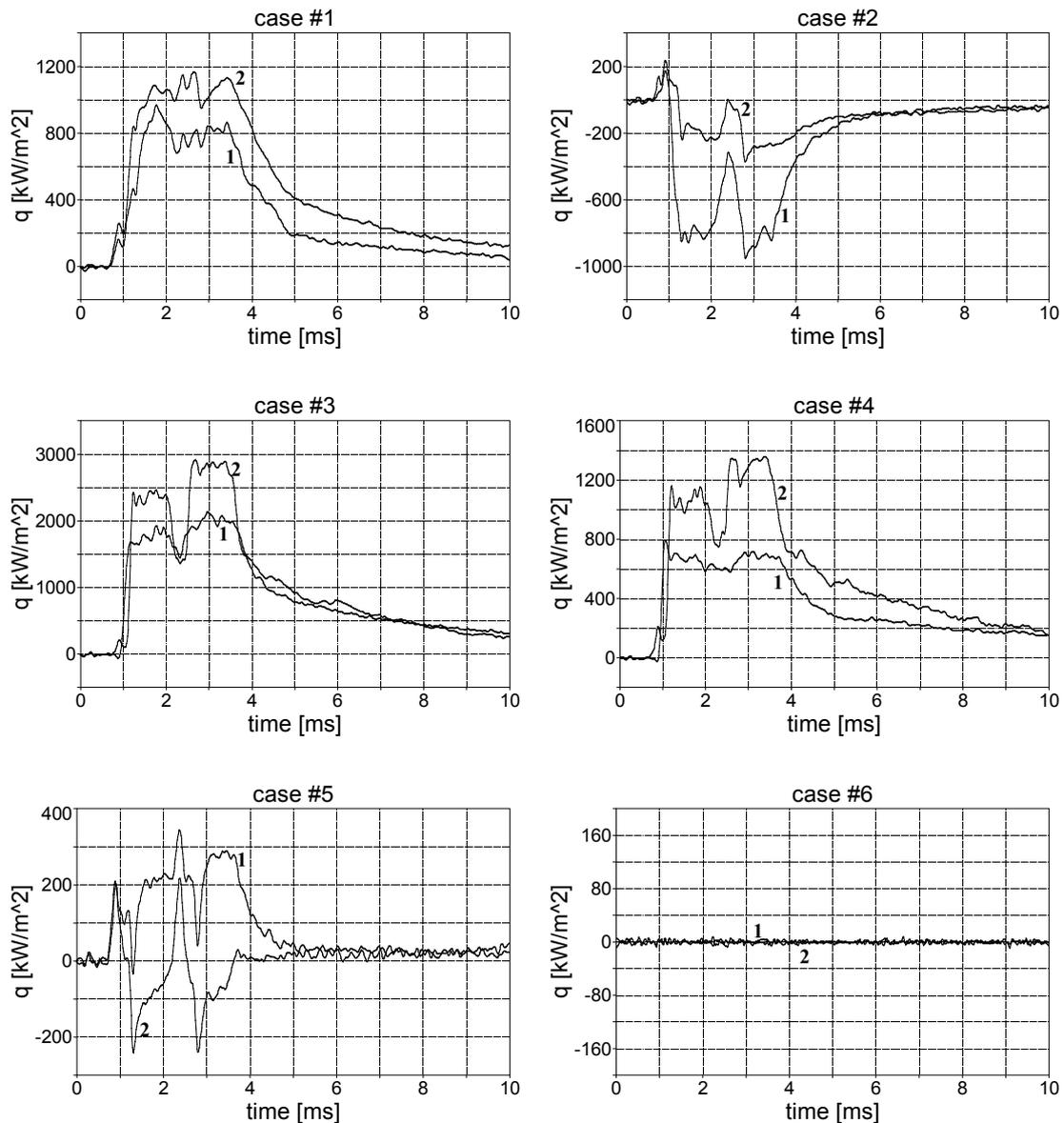


Fig. 2. Calculated heat flux densities on the wall surface for the selected cases; 1 – at the point on the jet axis, 2 – in a distance of 6 mm from the axis

In the case #1 the wall temperature was higher than the initial fuel temperature but the spray wall heated the wall. It means that the fuel temperature increased in a contact with the hot air. The jet core was gradually colder. Experiment in the case #2 was taken in similar conditions except the wall temperature. The fuel was heated by the air but its temperature reached a level lower than the wall temperature. The heat flux reversed and the wall was cooled.

For higher air temperatures the increase of fuel temperature was so big that the heat flux reached very high levels in order of 3 MW/m² (case #3). Even when the wall temperature equalled 180°C the heat flux was about 1.4 MW/m² (case #4). These values referred to the measurements at

point 2. The jet core was significantly colder giving the heat transfer less intensive. Two consecutive injections were clearly visible.

Very interesting was the case #5 in which heating and cooling took place together although the heat transfer was not as intensive as in previous cases. In respect of high air pressure the spray penetration was reduced and less fuel with lower velocity reached the wall. In spite of high air temperature (450°C) the jet consisted of cold droplets causing sudden fall of heat fluxes down to negative values.

The last case (#6) was selected to show that for certain conditions the heat transfer between the jet and the wall did not appear or could be very low, indicating that the fuel and the wall had the same temperature.

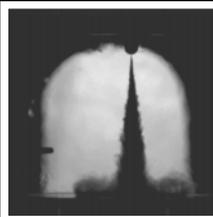
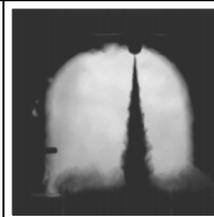
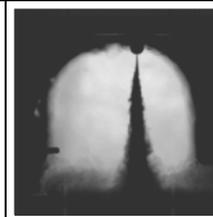
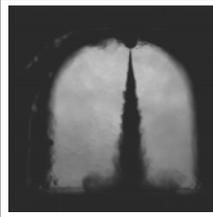
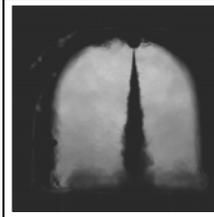
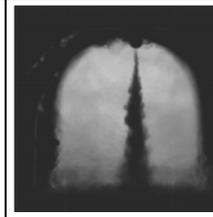
Case #3				
Case #5				
Time after start of injection	308 μs	616 μs	924 μs	1232 μs

Fig. 3. Spray behaviour and development of secondary flow along the wall surface

Heat transfer in the wall-jet interaction is a complicated phenomenon and depends on many different processes as a jet formation, mixing with a hot air, evaporation of a fuel and developing of secondary flow along the wall surface. Very important is knowledge of a spray structure, size and distribution of liquid droplets and their velocity. Fig. 3 shows the spray behaviour captured with the high-speed camera for two cases. The differences are obviously visible. In the case #3 the jet was thicker and earlier reached the wall then in case #5. There were also differences in thickness and optical densities of the secondary flow. Other advanced optical methods together with heat flux measurements might be needed to investigate all mentioned above phenomena.

5. CONCLUSIONS

The conducted experiments have showed that the coaxial thermocouples were very suitable for measurements of surface temperatures and calculations of local heat fluxes. They had short response time and reasonable thermoelectric force. The only problem was high sensibility for external electromagnetic noise but averaging experimental data for several consecutive measurements could solve it.

The heat transfer in the jet-wall interaction had different patterns depending on the measurement conditions. The heat fluxes ranged from values of order -1 MW/m^2 for cooling and up to 3 MW/m^2 for heating the wall. In some cases the heat flux was low or even decreased to almost zero, indicating that the fuel and the wall had the same temperature.

The fuel in the spray quickly exchanged heat with surrounded air and if the air temperature was higher than the wall temperature heat was transferred to the wall. But in some conditions fuel droplets remained cold causing sudden drop of heat flux down to negative values.

The heat transfer resulted from several processes as a jet formation, mixing with a hot air, evaporation of a fuel and developing of secondary flow along the wall surface. Further investigation of the heat transfer needs measurements of a spray structure, size and distribution of liquid droplets and their velocity.

6. ACKNOWLEDGEMENTS

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