

Gasoline Wall Films and Spray/Wall Interaction Analyzed by Infrared Thermography

Florian Schulz and Jürgen Schmidt
Otto-von-Guericke-University Magdeburg

Andreas Kufferath and Wolfgang Samenfink
Robert Bosch GmbH

ABSTRACT

Due to the principle of direct injection, which is applied in modern homogeneously operated gasoline engines, there are various operation points with significant particulate emissions. The spray droplets contact the piston surface during the warm-up and early injections, in particular. The fuel wall films and the resulting delayed evaporation of the liquid fuel is one of the main sources of soot particles. It is therefore necessary to carry out investigations into the formation of wall film. The influence of the spray impact angle is of special interest, as this is a major difference between engines with side-mounted injectors and centrally positioned injectors.

This paper describes an infrared thermography-based method, which we used to carry out a systematic study of fuel deposits on the walls of the combustion chamber. The boundary conditions of the test section were close to those of real GDI engines operated with homogeneous charge. We took the measurements under normal ambient conditions, substituting the piston by a heated plate and positioning an infrared camera underneath it. The single component fuel, n-heptane, was injected using a high-pressure multihole injector. The influence of four test parameters was examined - the wall temperature, the injection pressure, the distance between nozzle and wall and the spray impact angle.

The results we obtained include the heat flux at the spray impingement zone, the wall film area and the wall film mass. The heat flux at the spray impingement zone leads to a considerable decrease in the temperature of the wall surface and is influenced by all test parameters. The effect of the test parameter on the wall film area is not identical to that of the wall film mass. For this reason, the amount of fuel deposits is not proportional to the area of the wall film. High injection pressures and impact angle adjustment, in particular, can help to reduce the wall film mass.

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INTRODUCTION

Spray/wall interaction plays an important role in the process of mixture formation in gasoline engines with direct injection. When there is insufficient time for the spray droplets to evaporate completely, the liquid fuel impinges on the cylinder wall or the piston surface, leaving deposits on the surfaces of the combustion chamber. Generally speaking, the time remaining until ignition is too short for residue-free evaporation. A wall film represents a fuel rich zone and is the cause of soot particle emissions. It is for this reason that we decided to take a close look at the relevant processes.

To obtain a basic understanding of the physical relationships, the droplet/wall interaction is studied in detail. Numerous experiments have been performed regarding the water droplet impact on cold walls and succeeded in distinguishing three

basic phenomena: the droplet can stick to the wall, it can rebound from the wall or it can disintegrate into smaller pieces. To delineate the so-called impact regimes from each other, recent literature [1, 2] used the dimensionless K number as the splashing threshold parameter:

$$K = Oh^a \cdot We^b \quad (1)$$

This is a function of the Ohnesorge number (Oh) and the Weber number (We) with dimensionless exponents a and b dependent on the author:

$$Oh = \sqrt{We} / Re \quad \text{and} \quad We = \rho \cdot v^2 \cdot D / \sigma$$

while the Reynolds number (Re) is:

$$Re = \rho \cdot v \cdot D / \mu \quad (3)$$

The empirically found K number is integrated in most spray/wall impingement models used in CFD. The validity of the K number is however criticized, because the values of the splash threshold found by different authors differ widely [3]. This might be due to the fact that the influences of all boundary conditions are not yet fully understood.

The wall temperature has a significant influence on the droplet/wall interaction. Bernardin [4] describes the changing impact phenomena on reaching the saturation, Nukiyama and Leidenfrost temperatures respectively. A heat transfer is also generated between the liquid and the solid wall at higher surface temperatures [5]. These heat fluxes are of special interest since they cause the surface temperature to decrease.

In addition, the droplets can impinge on a wall that is already wetted. Yarin and Weiss [6] analyze the splashing behavior of single droplets. The cause of an existing liquid film is usually the former presence of droplets. This explains why experiments have also been carried out with droplet chains and multiple droplet impact [7]. Roisman [8] gives an overview of the influence the height of the film has on the liquid deposits.

Moreira et al. [9] point out that the models obtained from single droplet experiments yield insufficient results in spray simulations. It is particularly important to bear in mind the intensive interaction between the primary spray droplets that arrive and the secondary droplets leaving the wall surface. That is one reason why various experiments have been performed on spray/wall interaction. These studies focus on characterizing the secondary droplets [10] and the liquid deposition on a cold wall [11]:

$$m_{\text{deposition}} = m_{\text{primary}} - m_{\text{secondary}} \quad (4)$$

The developing wall films are of major interest for spray applications in GDI engines. Basically, there are two common methods for studying wall film behavior. The liquid is injected on to a roughened quartz window in order to apply the Refractive-Index-Matching technique (RIM) introduced by Drake et al. [12]. The ratio between the film height and the scatter light makes it possible to determine the height distribution of the film. This method is limited to very thin wall films. Another method that is not limited to any thickness of film uses the Laser-Induced-Fluorescence (LIF) signal of a liquid film to obtain the required film height information [13]. In order to avoid the spray droplets interfering with the signal, both the source of the exciting radiation and the detector for the fluorescence signal are located beneath a quartz window. The wall material constitutes a serious limitation in the case of each

of these two methods, however. It is hardly possible to control the temperature of the quartz window and the thermal conductivity is far below the piston material.

At the same time the spray/wall interaction was studied for the purpose of cooling processes [14]. Water for temperatures above Leidenfrost point was of special interest. Due to the use of thin film and other local sensors, it was possible to determine the transient wall temperatures and heat fluxes.

Since the surface temperature has a substantial influence on the spray/wall interaction [15] and the film evaporation, it might be of interest to conduct investigations that provide information on both the geometrical spray impact and film distribution and the occurring heat fluxes. With the help of the infrared method applied in this paper, it is possible to determine the uneven wall temperature gradients without touching them but with a high spatial and temporal resolution. This measuring method allows systematic measurements over a wide range of parameters. The results, which are suitable for the characterization of fuel films, allow the validation of simulation models.

SET-UP AND METHOD

The present study focuses on basic research into the spray/wall interaction and fuel wall films using infrared thermography. Applying spray to a heated plate at different boundary conditions accordingly simplifies the injection process of the real homogeneously charged Otto engine. Figure 1 illustrates the position of the IR8800 infrared camera underneath the sheet [16]. Its spectral range is 2 - 5.7 μm with a maximal geometric resolution of 640×512 pixels and a thermal resolution of less than 0,02 K. For the experiments the infrared recordings were taken with 800 Hz and a resolution of 0.31 mm^2/pixel .

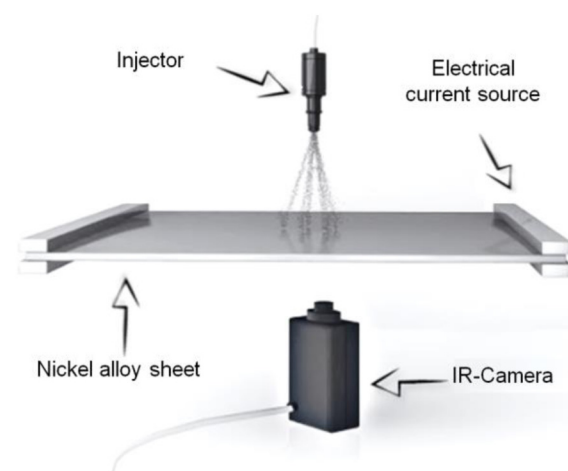


Figure 1. Schematic experimental set-up.

The electrically heated plate measures 100 × 150 mm^2 , consists of the nickel alloy Inconel 600 and has a special graphite coating with the thickness of 40 μm at the back to achieve a high emissivity. Due to its high thermal resistance Inconel 600 can be heated by means of the electrical power

supply. By comparison, aluminum would take an electric current over 30 times more powerful in order to induce the same degree of heat. The sheet is accordingly set to a constant temperature value prior to spray impact. The material properties of the sheet compared to a standard eutectic alloy for GDI pistons are listed in Table 1 [17]. From the point of view of heat conduction, the influence of the differences in the heat capacity almost completely offsets the density, but the higher thermal conductivity of the aluminum alloy will produce a better heat transport to the surface, which in turn will make the fuel deposits evaporate faster. So the current experiments will not exactly match the processes on a real piston. Thanks to numerical simulations, however, it is possible to transfer the effects found with the help of the IR experiments, such as the heat fluxes, to a different material. It is consequently possible to issue statements for other boundary conditions.

Table 1. Material properties of Inconel 600, piston material and coat.

Properties (at 298K – 371K)	Inconel 600	Eutectic Alloy AlSi12CuMgNi	Graphite Coat
Density [kg/m ³]	8470- 8396	2700	1791
Electrical resistance [n·Ω/m]	1030- 1060	28,2 (Al)	–
Heat capacity [J/kg·K]	444- 492	960	1225
Thermal conductivity [W/m·K]	13.6- 18.1	149	0.406
Emissivity	–	–	0.9

We tested sheet thicknesses between 0.1 mm and 0.3 mm in preliminary experiments. The thickness should be kept to a minimum, as it is in a square relationship to the permeation of the temperature signal. Reducing the plate thickness also increases the amount of partial reduction in plate temperature, thus lowering the heat input into the wall film. In the present study, we applied a plate thickness of 0.1 mm. This ensures a good balance between the signal permeation time and the internal energy.

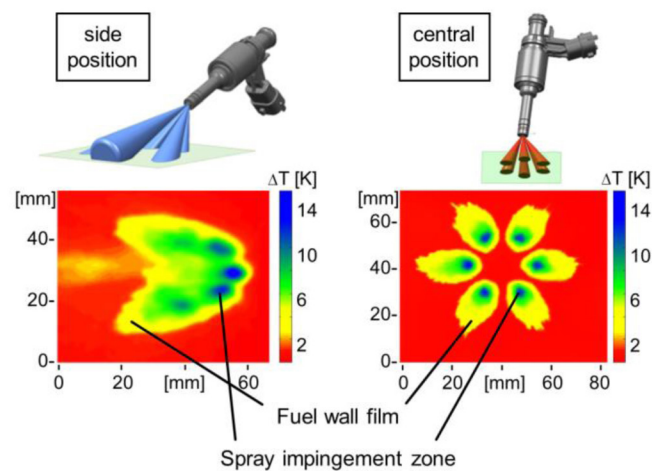


Figure 2. Fields of temperature differences: comparison of a side mounted injector and central positioned injector.

Figure 2 shows an example of the images obtained using the IR method. The initial wall temperature was set to 353 K, the fuel was injected at 15 MPa and the distance to the wall was 15 mm (left) and 25 mm (right). Instead of the raw IR temperature data we used the fields of temperature differences for visualization and later calculation purposes. These reflect the decrease in temperature at the back of the sheet and are calculated by subtracting the instantaneous temperature field from the stationary initial temperature field before starting the injection process.

$$\Delta T(x, y, t) = T(x, y, t) - T_{\text{stat}} \quad (5)$$

Due to its use in the experimental evaluation, it is possible to achieve a relative independence from the emissivity at T_{stat} and thus a high level of accuracy. The uncertainty of the temperature differences is in the range of the thermal noise of the camera of about ± 0.2 K.

We plotted Figure 3 to illustrate the temperature distribution inside and underneath the sheet. These temperature curves were derived using a direct numerical algorithm with COMSOL Multiphysics. As in the real experiments, we contemplated a 100 μm Inconel 600 sheet with the 40 μm graphite coating. To imitate the spray/wall interaction, we applied a constant heat flux to the top of the sheet for an injection duration of 1.5 ms. The heat flux of -3.1 MW/m^2 that was employed is an average value for the spray/wall system under consideration, with an initial wall temperature of 353 K and an injection pressure of 15 MPa. The top and back temperatures converge after about 16 ms. Here the temperature simulation clearly shows that the temperatures measured on the coated back do not match the top surface temperatures. That is important for the evaluation of the experimental data. An inverse heat transfer calculation is necessary in order to find the top surface temperatures from the measured temperature fields. We used a simplified approach, as described in [18], in the following analyses. Here the course of the mean values of parts of the temperature fields, e.g. the spray impact zone, was compared to results from a conduction simulation. In an iterative process, we adjusted the heat fluxes applied to the surface of the sheet in the simulation until the simulated temperature response matched the measurements. As a result, we obtained the temperatures and heat fluxes on top of the sheet.

As mentioned above, the behavior of the top surface temperature depends on the thickness of the sheet. We found further important information in this respect by means of the simulation. The top surface temperature is independent of the sheet thickness for the duration of spray impingement and wall film propagation. After about 2 ms, the temperature signal reaches the reverse side of the sheet and no additional heat can flow to the surface from below, as it would in a 3-dimensional body. That is why the surface temperatures in the experiments are lower than those on the surface of a half-space for longer-lasting experiments like measuring the

film evaporation. But heat is still transferred to the wall film, except with a smaller temperature difference as driving force. In addition, the electrically induced heat replaces part of the missing conduction from below. All this behavior is fine for basic investigations, since the results can be used in further simulations. In these calculations, the correlation found between the surface temperatures and the heat fluxes that take place can be assumed to approximate the surface temperatures for a different material or different geometries.

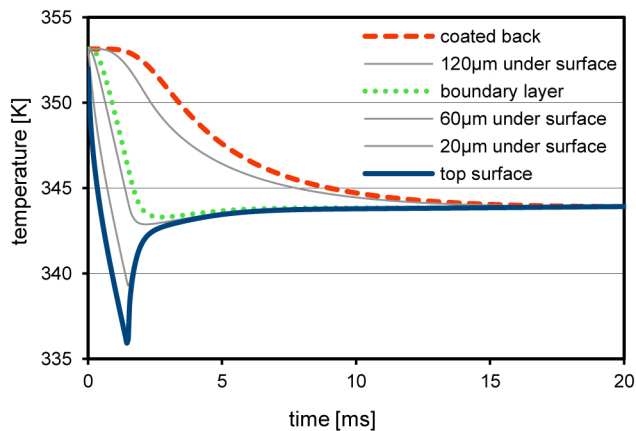


Figure 3. Simulated temperatures within a 100 μm thick nickel alloy sheet with a 40 μm coating on the back due to a constant heat flux of 3.1 MW/m^2 with a duration of 1.5 ms.

Test Parameter and Injector Positioning

The effect of injector positioning on the wall film is one central aspect of this paper. As seen in Figure 2, changing the position of the injector may produce a completely different wall film. The blue (dark) areas with maximum temperature decrease are caused by the direct spray impact. Because of the spray impulse that occurs during the injection process, the majority of adhering fuel is driven forward on to the surface. This wall film forming shadows in the yellow (light) regions.

To consider the different injector positions in the experiments, we varied the impact angel of one spray jet between 30° and 90°. We also examined the injection timing. To this end, we set the distance between nozzle and wall at 15 mm, 25 mm and 50 mm, representing early, average and late injection timing. The position of the injector in relation to the sheet is displayed in Figure 4. The distance between the nozzle and the wall does not describe the distance perpendicular to the wall, but defines the length of the path of the spray jet from the nozzle to the wall.

Only the influence of the one spray jet marked in red (Fig. 4) is of interest. Figure 5 shows the fields of temperature differences corresponding to Figure 4. The spray impact region of this spray jet is highlighted by a white circle in the fields of temperature differences. These images were captured at an initial wall temperature of 353 K and an injection pressure of 15 MPa.

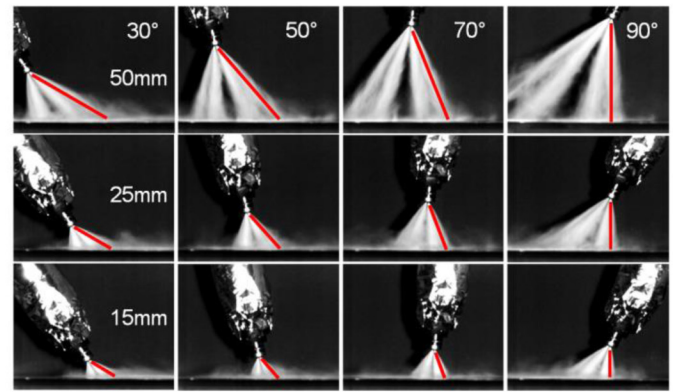


Figure 4. Injector positions side view.

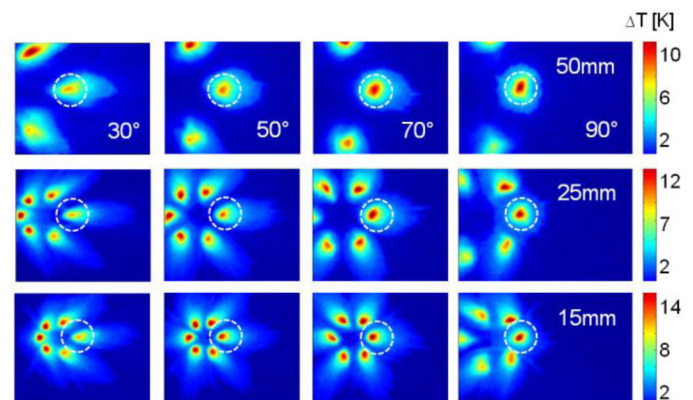


Figure 5. Fields of temperature differences for different injector positions.

Beyond the location of the injector, the wall temperature was varied because previous measurements [10] exerted a dominating influence on the initial sheet temperature. This is due to the different heat transfer patterns, namely the film evaporation regime, the nucleate boiling regime and the film boiling regime. Piston surfaces can reach temperatures across all of these boiling regimes. Wall temperatures remain low, particularly during the cold start and the automatic engine start/stop. During operation, the piston temperature depends on the load and reaches values between 410 K and 450 K [21]. This temperature range corresponds to the transient region between Nukiyama and Leidenfrost point for many gasoline substituting single component fuels. In that range of temperature a little change of the wall temperature causes a significant change of the heat flux. This is one reason why the fuel deposits on the surface of the piston are difficult to determine through simulation. For example, there is no wetting of the wall above the Leidenfrost temperature, but the surface temperature decreases, due to high heat fluxes during injection. Following droplets will stick to the wall and create a film. In our analysis these occurring heat fluxes were accordingly calculated for the different boundary conditions. In the experiments, the initial sheet temperature was set to values between 353 K and 533 K.