Characteristics of a Gasoline Spray Reflected from a Wall after Impingement

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Abstract

The results of experiments carried out on a real gasoline spray impinging on a wall under simulated engine conditions are reported. The reflected drop size and velocity distributions were characterized with Phase Doppler Anemometry measurements. A sensitivity analysis was carried out to investigate the influence of the surface structure and wall temperature on the impingement and secondary atomization processes. The drops reflected from a rough surface were found to be smaller than those reflected from a smoother surface. There was also a tendency for drops to leave the rough surface with a smaller reflection angle. Furthermore, the reflected drop size distribution was dependent on the wall temperature. The wall temperature also affected the velocity of the reflected drops.

1. Introduction

One approach to decrease the fuel consumption of spark ignition (SI) engines is to operate the engines in a lean stratified charge mode, using direct injection. The distinguishing principle of the direct injection stratified charge (DISC) SI engine is that, ideally, the mixture around the spark plug should be stoichiometric or slightly rich, while the rest of the combustion chamber should be filled with pure air or air diluted with recycled combustion products. This differs from the homogenous port fuel injected (PFI) SI engine, in which the mixture composition in the combustion chamber is uniform and globally stoichiometric or close to stoichiometric. Currently, several different techniques are used to achieve charge stratification, the wall guided system being the most common. In this combustion system the air/fuel mixture is directed towards the spark plug with the aid of the piston. One of the drawbacks of DISC engines compared to the conventional PFI SI engines is the relatively high levels of unburned hydrocarbons (UBHC) they emit. The reason for this is that the atomization of the fuel spray is poor and relatively large drops are formed. There is not enough time for the largest drops to evaporate and some of them impinge on the piston surface, forming a wall film. The wall film creates an under-mixed area outside the ignition limits and the unburned fuel leaves the engine in the form of UBHC emissions. In this fuel-rich area there is also a risk of soot formation.

When a drop impinges on a surface there are three different possible outcomes: the drop may be deposited on the surface, it may either completely or partially rebound from the surface and/or there may be a complex process whereby the drop splashes and breaks up into a number of secondary drops (secondary atomization). The results of the impact depend on several physical and dynamic parameters. If there is a pre-existing wall film covering the surface or the surface is heated, additional outcomes are possible.

In attempts to further develop DISC SI engines Computational Fluid Dynamics (CFD) approaches are being used. However, CFD often fails to provide sufficient accuracy, mainly because the sub-models used to simulate the physical phenomena are insufficiently accurate. Therefore, there is a need for new, more accurate models. To derive a model of wall effects, more detailed knowledge about the influence of the parameters influencing the spray-wall impingement process is needed.

2. Experimental set-up

To investigate how different wall properties influence the impingement process of a gasoline spray, experimental investigations were carried out in a constant pressure spray chamber, so there was a continuous stream of pressurized air flowing through the chamber during the experiments. However, the velocity of the air in the measurement section of the chamber is relatively low (around 0.1 m/s), which can be neglected compared to the velocity of the injected spray. The incoming air can be heated up to 900 K, which allows experiments to be carried out in simulated engine conditions. The boundary conditions in this study were a gas pressure of 0.5 MPa and a bulk air temperature of 500 K, simulating the conditions in the DISC SI engine at the start of injection (SOI). The spray chamber is equipped with three quartz windows to allow optical access. The windows are placed in configurations suited for Phase Doppler Anemometry (PDA) measurements (giving the possibility to use 35° or 65° off-axis angles).
The fuel injection system consists of a Bosch 6-orifice gasoline injector. The rail pressure was 10.0 MPa, provided by a high-pressure fuel system consisting of an electrically driven Bosch high-pressure gasoline fuel pump running at constant speed. The injector was controlled by an injector power stage built in-house. The injector and the PDA data acquisition system were synchronized by a Stanford Research DG535 pulse generator. The fuel used was iso-Octane (2,2,4-triethhylpentane, C_8H_{18}). This fuel is commonly used in gasoline experiments because its boiling point is 99°C, which is close to the 50% evaporation point of gasoline.
To investigate the impingement process a flat wall was mounted in the spray chamber downstream of the injector nozzle. The wall was aligned so that one of the spray plumes would impinge on the wall, see Figure 1. The drop sizes and velocities were characterized using Phase Doppler Anemometry. Experiments were carried out in four different parallel planes at different heights over the wall. However, the results show that the impingement process only occurs close to the wall, as also found by Meingast et al. [1]. Therefore, only results from one measurement plane, located 0.5 mm above the wall are presented. The location of the final measurement point was limited by the optical access in the spray chamber. The wall was mounted with an inclination angle of 9 degrees relative to the horizontal plane. With this set-up the spray impingement angle is 30 degrees. The point where the center of the spray plume impinges on the surface is referred to as the impingement point. This point differs slightly from the location where the theoretical spray plume centerline crosses the wall. Results are presented from two measurement points, one upstream and one downstream of the impingement point. The positive axial velocity component that is discussed in this report is defined in the direction of the y-axis and the positive radial component is defined in the x-axis direction, see Figure 1.

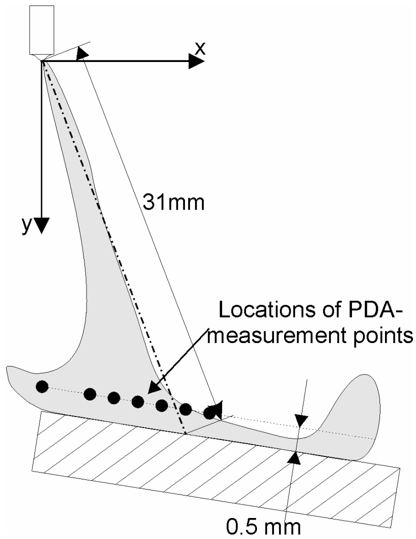

Figure 1: The wall aligned with one of the spray plumes of the injector. The positions of the PDA-measurement points are also shown.

The wall is heated by the surrounding air and is equipped with a water cooling system, so it is possible to control the surface temperature independently. The wall temperature is measured with a thermocouple mounted 1 mm below the surface. In this study the wall temperature was altered and experiments were performed at wall temperatures of 381 K, 435 K and 489 K. These temperatures correspond to 0.7 T_{crit}, 0.8 T_{crit} and 0.9 T_{crit} where T_{crit} refers to the critical temperature of iso-Octane (543K). Two different surface structures were also tested in this study. The first surface, called casted, has a very irregular structure created by the casting process. This surface has a roughness (R_z) value equal to 15.42 μm. The second surface, called machined, has a more regular surface structure with an R_z-value equal to 13.42 μm, see Figure 2. Both surfaces have a roughness of the order, in size, of the impinging drops. The casted surface has a smoother surface structure, although its R_z-value is larger, while the machined surface has sharp local changes in its structure. The effects of the different surfaces were studied at a surface temperature of 381K and the wall temperature study was carried out solely with the casted surface.

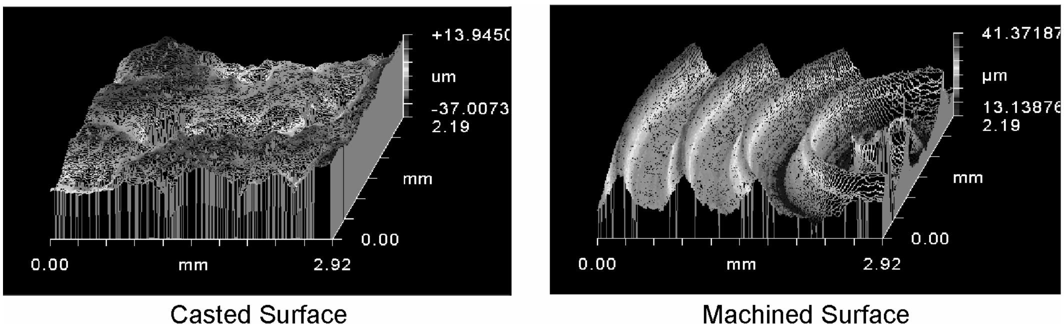

Figure 2: Magnifications of the two different surfaces used. Images from the surface characterization produced by light interferometry [2]**.**

The PDA system used to characterize the drops was a 2-D TSI/Aerometrics Phase Doppler Particle Analyzer (PDPA) with a TSI FSA-4000 processor. This system enables two velocity components to be determination, together with the diameter of a drop, simultaneously. The system also samples the arrival time for the drop when it passes through the measurement volume, which is created by four intersecting laser beams. The length of the ellipsoidal measurement volumes is of the order of 150 µm. Because of the size of the measurement volume and the nature of the spray, one injection event does not provide sufficient data, so the results consist of data collected over several hundred injections at each measurement point.

The laser light source was a Coherent Innova 90 Argon-Ion laser. The system was set-up in a forward scattering configuration with a collection angle between the transmitter and the receiver of 115 degrees. The transmitter's focal length was 500 mm and the receiving optics had a focal length of 300 mm. The optical equipment was mounted on a 3-D motion traverse system that was controlled by the PDPA acquisition software.

3. Experimental Results and Discussion

Since all processes involving gasoline engine sprays are transient in nature most of the results are provided as a function of time. At t = 0, the electrical signal required to drive the injector is initiated. From that point until the discharge of fuel begins there is a delay of 0.35 ms. The main injection phase ends about 4.5 ms after the initiation of the injector signal. The injector used in this investigation was prone to severe post-injection. This led to differences in injector behavior following the main injection between different experiments. The post-injection phase consisted larger drops and showed more injection-to-injection variation. Therefore, only results obtained during the main injection phase, i.e. times from 0 ms to 4.0 ms after the start of injection, are presented in this study.

In Figure 3 the influence of the wall on the size distribution of the incoming spray is shown. The free stream spray size distribution is compared to the size distribution of two sprays impinging on the wall with different surface structures. When processing the data, drops with negative axial velocity were considered as reflected drops. As can be seen in Figure 3 there are no major changes in the size distribution because of the wall. Therefore, it can be concluded that there is no major increase in drop coalescence because of the wall. Since the size distributions for the two cases are so similar, the free stream case will be used below as reference for comparing incoming spray size distributions.

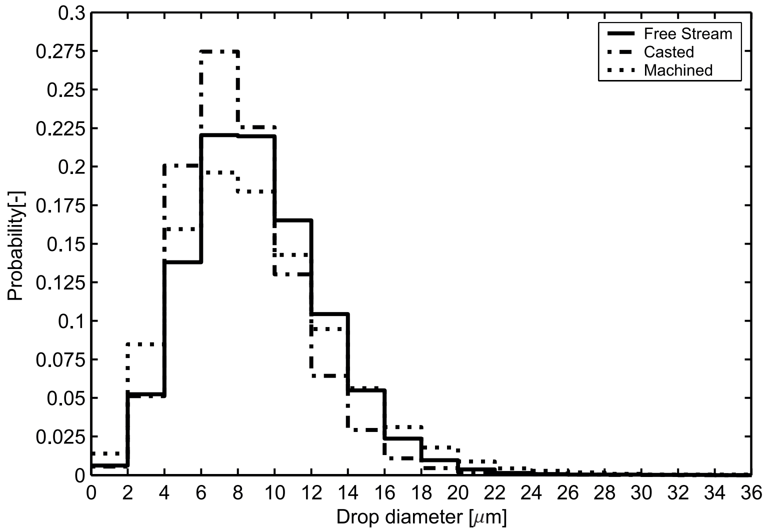

Figure 3: Drop diameter distribution of the free stream spray compared with the incoming drop diameter distribution in the presence of a wall.

Figure 4 shows the observed size distributions of the drops reflected from the wall compared with the incoming size distribution. Clearly, some break-up occurs at the surface since the size distribution of the reflected drops from the two different surfaces shifted towards smaller diameters compared to the size distribution of the incoming drops. Comparing the two different surface structures, the drops from the machined surface had the smallest size distribution. These findings are consistent with studies of single drops impinging on surfaces with different properties reported by Mundo et al. [3]. In their experiments the surface with greater roughness was associated with greater secondary breakup from the wall and thus smaller secondary drops.

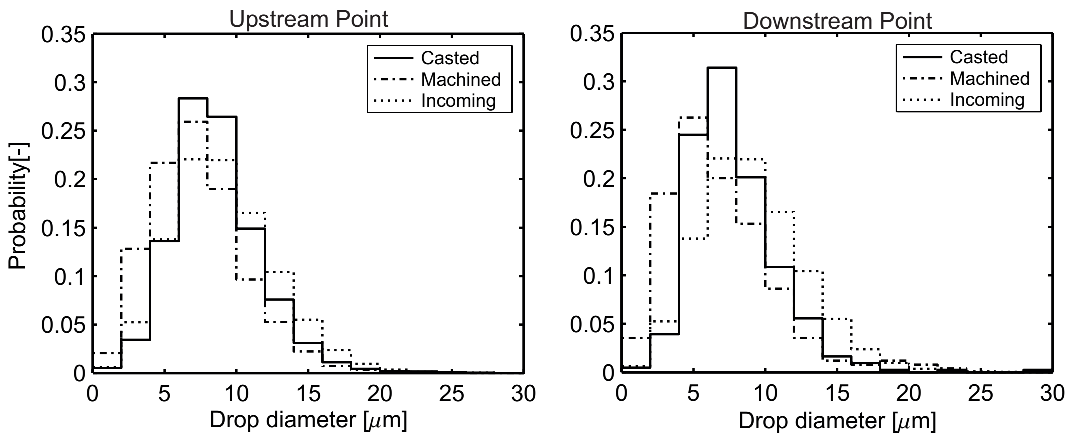

Figure 4: Reflected drop size distributions for the different surfaces. Results are presented from two measurement locations, one point upstream and one downstream of the impingement point.

Figure 5 shows the mean diameter of the incoming drops and the reflected drops plotted as a function of time from the start of injection (SOI). It is clear that the mean diameter of the incoming drops is more or less the same for the two cases. It is also apparent that the reflected drops have a smaller mean diameter than the incoming drops in both cases. Therefore, these data also indicate that the impingement of the spray results in a secondary atomization, although the differences are rather small.

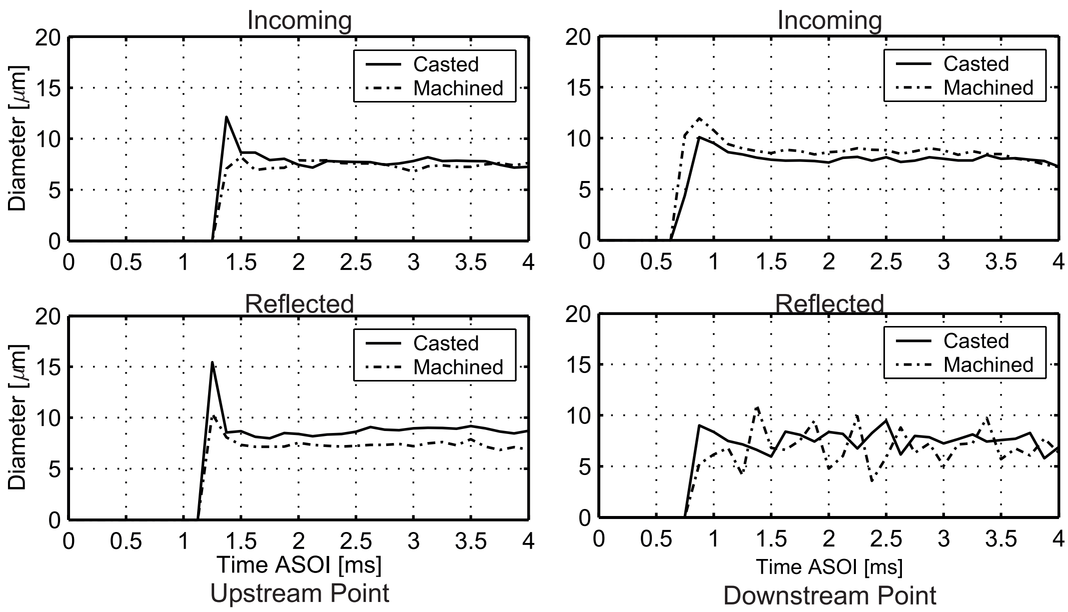

Figure 5: Time-resolved mean diameters for incoming and reflected drops for the two surfaces. Data obtained from one point upstream and one point downstream of the impingement point.

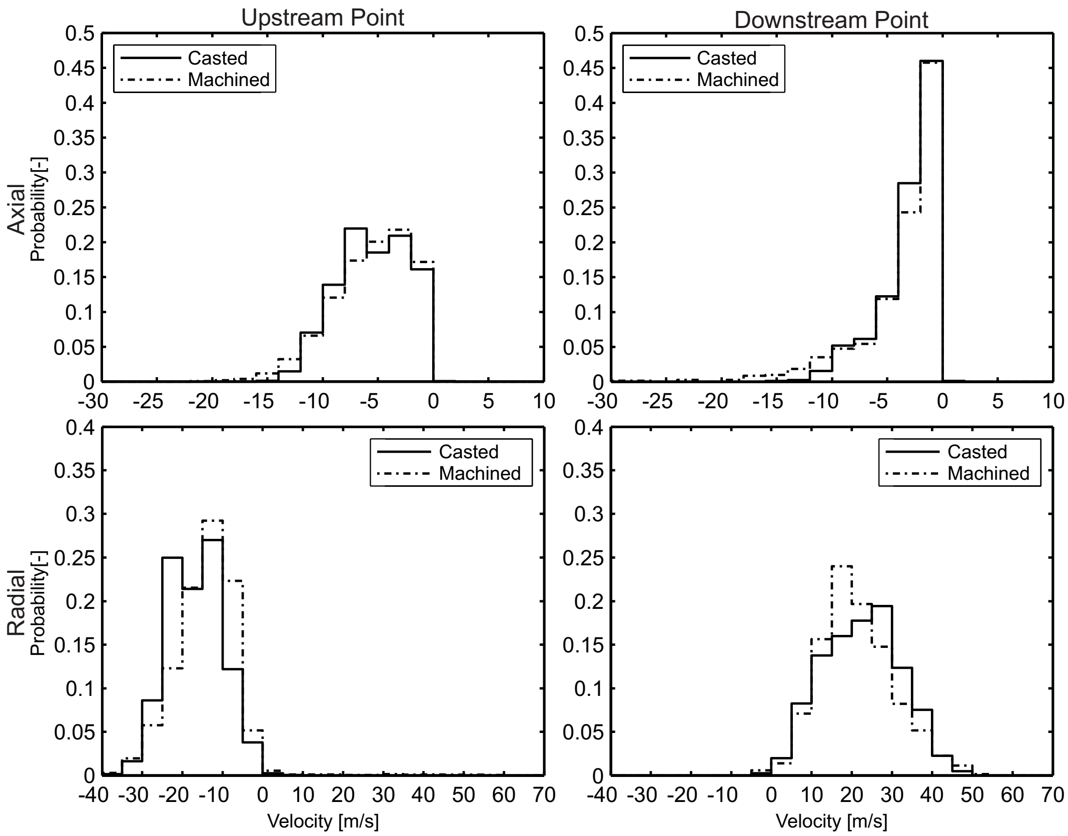

Figure 6: Velocity distribution of the drops reflected from the two surfaces for two different measurement points above the wall.

The data in Figure 5 show that the drops originating from the machined surface had a smaller mean diameter compared to those reflected from the casted surface. This demonstrates, again, that the breakup process was more intense from the machined surface. At the downstream point, the reflected drops mean diameter was fluctuating for both surfaces but it was less constant for drops reflected from the machined surface. This might be a result of a more irregular breakup process occurring at the rougher surface, as previously observed in the experiments carried out by Mundo et al. [3].

Figure 5 also shows that when the spray tip passes the PDA measurement volume, larger drops are detected in the impact area. These larger drops are probably due to coalescence between decelerating drops in the spray tip and drops from the spray. The coalescence process also influences the size of the reflected drops in the spray tip, which become larger than the reflected drops in the succeeding spray.
In Figure 6 the velocity distributions for the reflected drops are compared for the two different surfaces. The drops originating from the machined surface have a somewhat broader distribution of the axial velocity component and the velocity distribution of the radial velocity component is shifted towards lower absolute values compared to the casted surface. This indicates that the drops reflected from the machined surface leave the surface with a smaller reflection angle relatively to the surface normal, than drops reflected from the casted surface. This is, again, a result of more intense secondary atomization at the rougher surface, as also observed in the experiments described by Mundo et al. [3].

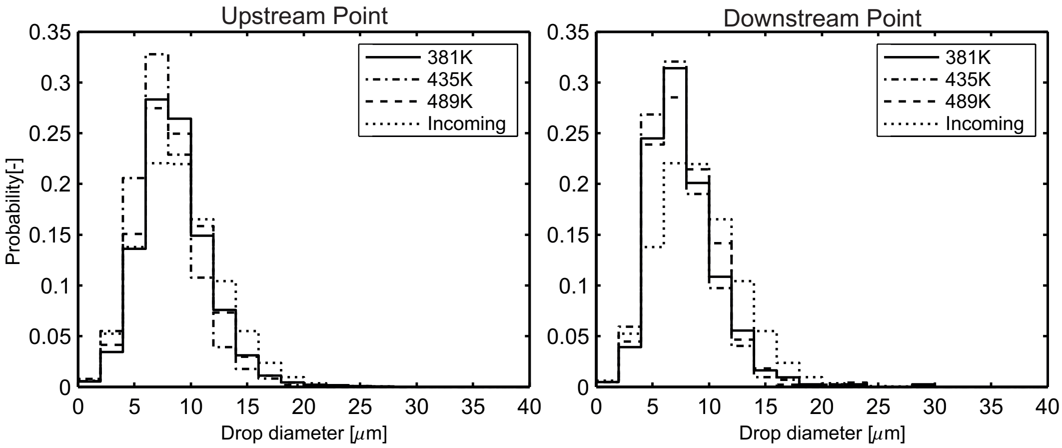

Figure 7: Reflected drop size distributions for surfaces with different temperatures compared with the reference size distribution.

The influence of the wall temperature on the size distribution of drops reflected from a casted surface is presented in Figure 7. The intensity of the breakup seems to be dependent on the wall temperature. The drop size distribution is shifted towards smaller diameters when the wall temperature is changed from 381K to 435K. However, even higher temperature seem to counteract increases in breakup, because the reflected drop distribution moves towards larger diameters when the temperature is increased from 435K to 489K. This may be a result of boiling phenomena occurring in the drop during the impingement. In experiments conducted by Cossali et al. [4] it was observed that the sizes of the secondary drops produced in the impingement process were dependent on the wall temperature. If the wall temperature is below the Leidenfrost temperature the liquid in the drop wets the surface and rapid boiling is observed in the drops. When the vapor bubbles erupt from the liquid interface of the impinged drop, small drops are produced. If the temperature was increased above the Leidenfrost point the impinged drop was no longer in contact with the wall. Therefore, it was only boiling in the liquid film that caused the spreading drop to explode into larger drops, compared to the drop sizes produced at lower wall temperatures.
Whether the change in the drop size distribution is a result of Leidenfrost phenomena or not is a matter of debate. In several studies [5-7] the Leidenfrost temperature has been shown to be dependent on surrounding conditions, surface conductivity and surface roughness. Therefore, it is very difficult to set any definitive, general limits for when the different phenomena described in [4] will arise. For a polished aluminum surface in ambient conditions the theoretical Leidenfrost temperature should be 420K for iso-Octane. However, for the conditions in which these experiments were conducted the Leidenfrost point would most probably be at higher temperatures [5-7].

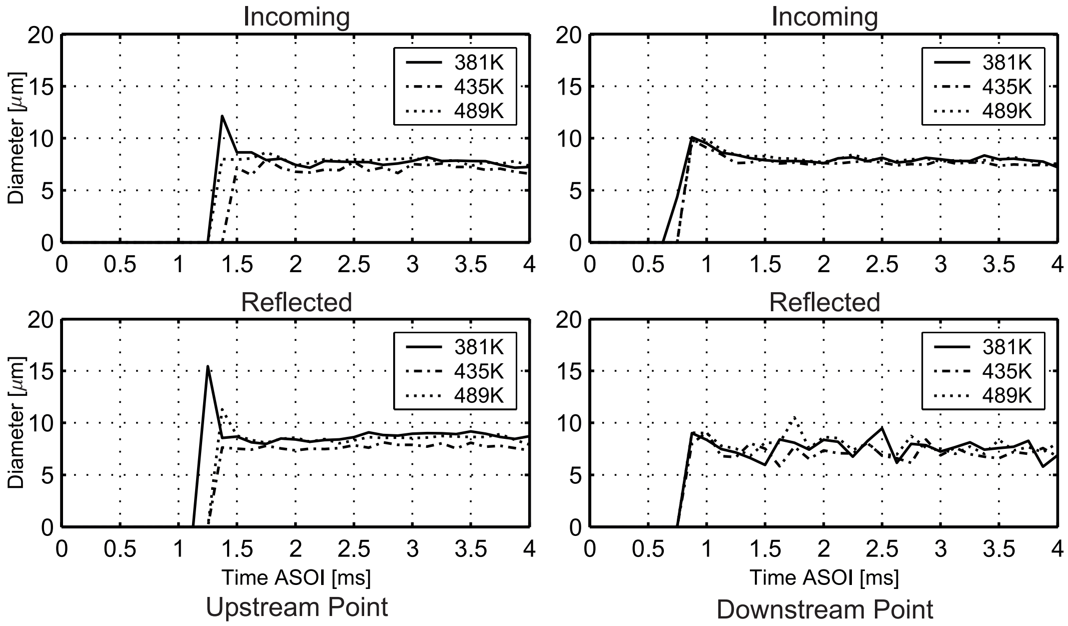

Figure 8: Time-resolved mean diameters for incoming and reflected drops for the three tested wall temperatures. Data obtained at one point upstream and one point downstream of the impingement point.

Comparison of the mean drop diameters of the reflected drops shows, again, that the intermediate temperature produced the smallest diameters, see Figure 8. The coalescence of the drops in the spray tip is also observed in these measurements.

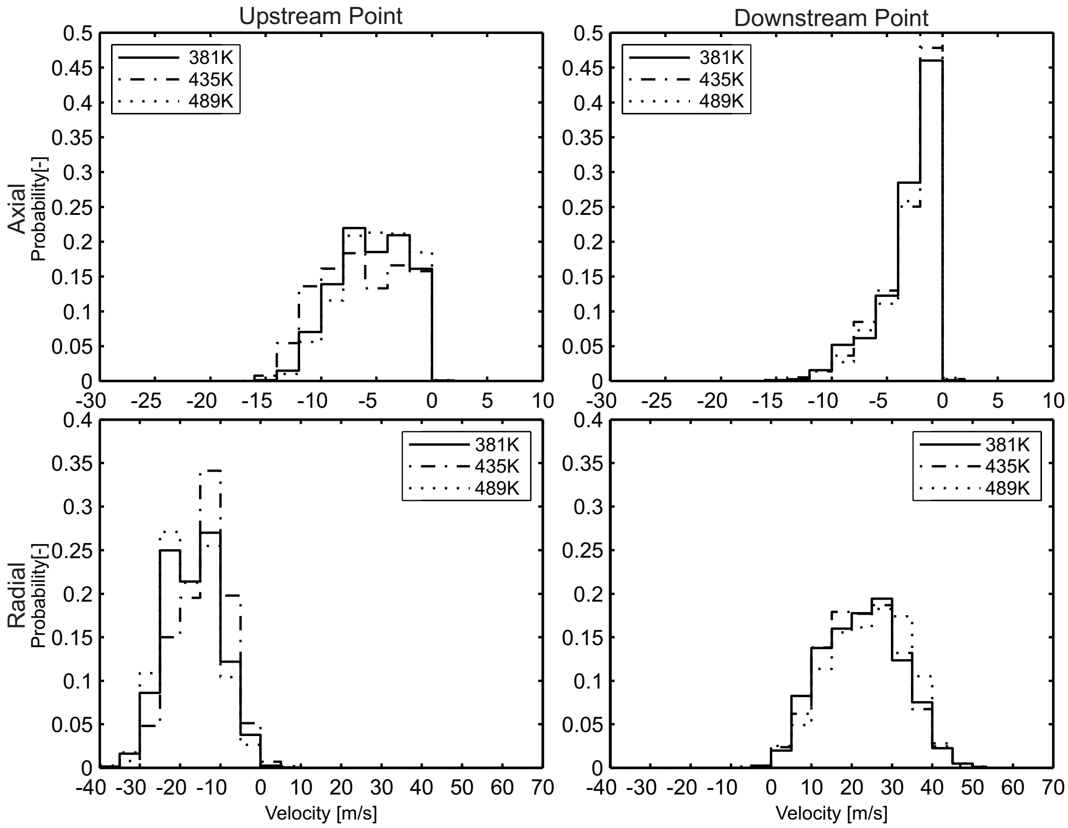

Figure 9: Velocity distribution of the reflected drops for the three wall temperatures. Results obtained at two different measurement points above the wall.

In Figure 9 the velocity distributions of the drops reflected from the wall at different wall temperatures are shown. At the two points, both upstream and downstream of the impingement point, it appears that there is weak dependence on the temperature. Considering first the axial velocity, is appears that the drops move fastest in the axial direction at 435K. When the temperature is further increased to 489K the axial velocity distribution is again shifted towards lower velocities. For the radial velocities the behavior is the opposite: the radial velocity at both points first decrease when the wall temperature is increased from 381K to 435K, but when the wall temperature is further increased to 489K, the radial velocity distribution is increased. This indicates that drops tend to leave the surface in a more tangential direction when the wall temperature approaches the Leidenfrost temperature. This, according to Cossali et al. [4], is related to the boiling regimes in the wall film.

4. Conclusions

In this study, experiments with an iso-Octane spray impinging on a heated surface under simulated engine conditions were carried out and the influence of different surface properties on the impingement process was studied. In the experiments the surface roughness and wall temperature were varied. When the surface roughness is increased the drop's diameter distribution shifts towards smaller diameters. The results also showed that the reflection angle decreases relative to the surface normal. The reflected drop size distribution also shows a dependency on the wall temperature. When the temperature is increased to 435K the diameter decreases and the distribution shifts to smaller drops. A further increase in the wall temperature increases the size of the reflected drops. This is believed to be connected with the boiling processes in the wall film. The wall temperature also influences the velocity components of the reflected drops.

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6. References

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