Thermal analysis of a GDI multi-hole spray footprint dynamics by phase-averaged Infrared thermography

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Abstract The research field of combustion optimization in modern engines adopting the gasoline direct injection (GDI) has been recently improved due to the strict regulations about pollutant emissions imposed by states’ laws. The droplet-wall interaction is significant influenced by the fuel injection pressure and the time-dependent temperature on the piston head whose quantitative knowledge is sparse. In the present study, the thermal analysis of an iso-octane spray footprint generated by a multi-hole GDI injector impinging on a thin Invar foil heated by Joule effect is performed by means of Infrared (IR) thermography. Starting from the fuel impact instant, several thermal images are acquired at different time delays employing a phase-averaged approach. In particular, a study on different injection pressures (10 and 20 MPa) and wall temperatures (366 and 473 K) at fixed nozzle-to-wall distance of 11 mm is presented. The unsteady thermal dynamics at the impingement is described by the two-dimensional temperature difference maps and the phase-averaged time dynamics of the temperature drop in the impact points.

Keywords: Spray-wall interaction, GDI engines, Infrared thermography

1 Introduction

Spray/wall interaction is crucial for both spray cooling and mixture formation in gasoline engines characterized by direct injection configuration. If the time between two ignitions is not sufficient, the fuel does not completely evaporate and deposits on the combustion chamber walls and on the piston head could originate. This likely happens when specific unfavorable operating conditions occur. As a matter of fact, a spray does not behave exactly as a summation of individual droplets since it is characterized by strong spatial and temporal interactions resulting in more complex physical phenomena. Hence, transfer of basic studies’ results is possible only up to a limited extent. Qualitative measurements dealing with spray impact have been proposed applying optical measuring methods like Schlieren imaging \cite{1}\cite{2}, Mie-scattering technique \cite{2}\cite{3}\cite{4}, Planar laser-induced fluorescence \cite{5} and Phase Doppler Anemometry technique \cite{6} but no details are provided about footprint and temperature drop on the impinged wall. Lately, IR thermography is being applied for measurements of temperature distribution of impinging sprays \cite{7}\cite{8}. The purpose of the present work is a further development towards the measurements of the thermal footprint of a spray impact employing the IR thermography with a phase-averaged approach.

2 Experimental set-up

A schematic of the experimental set-up is reported on Fig. 1a. The spray is generated by a solenoid-activated eight-hole direct-injection gasoline injector and its duration is equal to 1 ms. It is located 11 mm above the impingement wall made of Invar (50 $\mu$m in thickness) enclosed within an aluminum rigid frame and clamped as shown in Fig. 1b. A power supply provides 30.8 A and 52 A uniformly heating the foil by Joule effect at 366$\pm$5 K and 473$\pm$5 K respectively. In both the investigated cases, the Infrared camera acquires the radiation deviated by a mirror employing two different integration times equal to 150 $\mu$s and 30 $\mu$s with an optical path of 33 cm resulting in a spatial resolution equal to 2.35 px/mm. A total of 18 phases of the spray impingement are investigated for the phase-averaged analysis acquiring 125 repetitions of the spray impact assuming a fixed delay between the IR camera acquisition and the first droplet impact on the heated thin foil. The main frequency carrier, which corresponds to the IR camera acquisition frequency, is fixed to 25 Hz while the frequency of the fuel injection is fixed to 0.0625 Hz to guarantee the impinging wall thermal recovering between an impact and the next. The spray temperature and the environment pressure and temperature are kept constant at ambient conditions while two different injection pressures (10 MPa and 20 MPa) are investigated.
3 Results and discussion

In the following, a phase-averaged investigation of the spray impingement of an iso-octane spray on a heated thin foil is presented by analyzing the effect of the injection pressure and the wall temperature on the temperature difference distribution dynamics. The two-dimensional temperature maps reported in Fig. 2a are obtained by averaging 125 instantaneous thermal images of the spray impact subtracted of the immediately preceding background thermal image. They are referred to 1 ms after the impact event when the fuel injection terminates and the maximum heat is transferred from the plate to the impinging fuel.

A cooling pattern with eight plumes is present. For the lower wall temperature ($T_w = 366$ K), three different regions are clearly visible in the temperature maps demonstrating that the temperature spatial gradients are noticeably high. In the following, only a single cooling plume which is repeated eight times on a circumference is considered. The blue region is the coolest area whose centroid can be ascribed to the spray impact point. The warmer elliptically shaped surrounding area is representative of the fuel splashing over the wall promoted by the vapor film formed by the spray coalescence [9]. In this region, the temperature drop is not as high as in correspondence of the impact points but it is remarkable. Lastly, the yellow region is completely unaffected by the spray impact. By increasing the injection pressure from 10 to 20 MPa, a larger quantity of fuel impacts on the plate and at higher velocity. As a consequence, the temperature drop in the impingement points weakly drops of about 2 K and, in addition, the spatial extension of the plumes which surround them increases.

The effects of a higher wall temperature to $T_w = 473$ K are clearly visible in Fig. 2a. Firstly, the temperature drop magnitude is doubled in correspondence of the impact points and the radial spatial extension of the
plumes is reduced and never exceeds 5 mm. This phenomenon could be ascribed to the droplets rebound from the surface [9]. Increasing the injection pressure, the temperature drop dramatically increases of almost 20 K in respect with the previous case while the plumes extensions appears to be unaffected.

The time dynamics of the temperature drop in the impingement points are reported for the four investigated cases in Fig. 2b. The red plus and crosses represent the phase-averaged measurement points obtained by averaging the temperature drop in correspondence of the impact point of the eight plumes for each time delay (Δt) analyzed. Starting from the spray impact event, the relevant negative slope demonstrates how crucial the convective contribution provided by the impinging droplets is. As it can be noticed, the four curves show a similar trend up to 1 ms when the iso-octane injection terminates. As a matter, everything that comes after is just a direct consequence of this time frame. After 2 ms from the impact event, the slope approaches to zero value and then the trend assumes a slightly positive value after about 9 ms from the spray impact. From 2 ms to 20 ms, the four curves distinguish among themselves for the different quasi steady-state condition reached. The greatest temperature drop for the lower wall temperature is bounded between 13 K and 16 K for both injection pressures investigated. On the other hand, a higher wall temperature causes a remarkable increase of the temperature drop magnitude to almost 30 K which increases to 50 K with the application of a higher injection pressure.

In conclusions, the thermal data acquired during these preliminary investigations will be useful to focus the analysis on the heat transfer capabilities of such a device. As a matter, the designed experimental apparatus can be modelled as a heat transfer sensor [10] assuming the temperature difference of an isothermal surface as heat transfer driving source.

References


