Experimental analysis of a GDI spray impacting on a heated wall

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Introduction

The greater control on the in-cylinder air-to-fuel ratio gives gasoline direct injection (GDI) engines the possibility to operate at higher compression ratios with respect to port fuel injection (PFI) ones, hence to achieve different charge characteristics depending on the specific load or speed, as the homogeneous mode for stoichiometric operation or stratified mixtures for lean overall operation. Since liquid fuel is directly injected into the combustion chamber, the fuel spray characteristics strongly influence the process of fuel-air mixing and combustion [1]. One important challenge for the GDI technology is that while it is essential to have a more uniform in-cylinder fuel distribution for better preparation of the combustion, the time available for fuel atomization and air mixing is very limited. Therefore, rapid atomization and vaporization of fuel spray are highly desirable. A key feature for better atomization is the fuel injection pressure. A higher injection pressure facilitates a higher atomization degree of fuel and vaporization but, at the same time, creates an over-penetrating spray so optimization is required [2]. However, due to the short distance between the injector nozzle and the piston head/cylinder walls, at high-injection pressure the fuel may impinge on walls before a fully vaporization and mixing with the air. On one hand, the spray impact accelerates the secondary atomization; on the other hand, a thin fuel film is deposited on the surface of the piston and/or the cylinder wall and both soot and un-burned hydrocarbon (UHC) were experimentally observed [3-6]. Therefore, a great need to characterize the DISI gasoline spray-wall interactions in details arises, not only to understand the fundamental transport processes, but to provide data to validate CFD predictions, too, which have become essential in the design of DISI engines.
Aim of this study is a detailed understanding of the interaction between the injected fuel and a flat wall under engine-like conditions, observing both the liquid and the vapour phases as the surface temperature varied (room to 573 K) in a controlled environment.
A customized algorithm, able to catch the contours of the liquid phase and the vapour/atomized zone, was used to extract the diffusion and evaporation parameters that characterized the impingement of the fuel.

Material and methods

The tests were performed in a constant-volume combustion vessel optically-accessible through three quartz windows allowing the admittance to the investigated area. A single-component fuel was used as fluid: iso-octane. The chosen injector was a solenoid-activated eight-hole direct-injection gasoline injector from the Engine Combustion Network (ECN) effort on gasoline sprays (Spray G). The nozzle holes are equally spaced and are 165 μm in diameter, according to the specifications. The injector was located on the top of the vessel in a holder including a jacket for the temperature setting of the nozzle nose and connected to a chiller for fluxing a cooling liquid. The fuel was supplied through a common rail system, heated by an electrical resistance and controlled in temperature by a J-type thermocouple based system located in the rail. Both the injector and the fuel temperature were kept at 363 K. The experimental work was carried out at the room temperature and atmospheric back-pressure except for the setting of the impinged wall temperature. Characterization of the spray impingement on a wall was made by introducing an 80 mm in diameter aluminum flat plate into the vessel, positioned 21 mm downstream the injector tip and facing orthogonal to the injector axis. The plate was heated in the range from 293 to 573 K (T_w) by electric resistances and controlled in temperature by a J-type thermocouple located in its center at 1.0 mm from the wall surface. Moreover, the spray-wall interaction was studied for three injection pressures, 5.0, 10.0, and 20.0 MPa. An optical setup of simultaneous Mie scattering and schlieren imaging techniques was applied for the spray-wall interaction test by using a Photron Fastcam SA4 high-speed camera to acquire the liquid/vapour spray at 25,000 fps with an exposure time of 39.33 μs. The arrangement was capable to acquire alternatively schlieren and Mie-scattering images in a quasi-simultaneous fashion using the same optical path. This methodology allowed complementing the liquid phases of the impact, obtained by the Mie scattering, with the liquid/vapor ones collected by the schlieren technique for determining both the phases inside a single cycle. The camera used a Tamron 90 mm lens with f-stop 1-2.8, with a spatial configuration realizing a resolution of 6.5 pixel/mm. More details on the adopted hybrid optical setup were reported in [7]. A homemade algorithm for image-processing was performed using a customized procedure developed under MATLAB platform to treat the batch and to outline the contours of the images.

Results and Discussion

Figure 1 reports an impacting spray sequence at different wall temperatures (from 293 to 573 K) from Mie scattering (top) and schlieren (bottom) optical technique. The imagines refer to the time step of 480 μs after the impact and the injection pressure is 20.0 MPa. For each column the effects of the wall temperature can be evaluated on liquid phase from Mie-scattering images and on both liquid and vapor from schlieren ones.

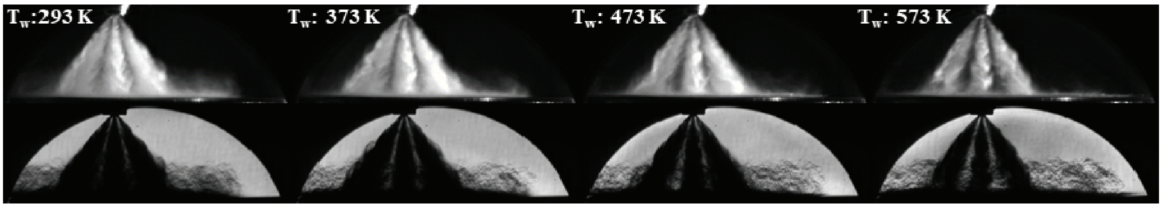

Figure 1. Mie scattering (top) and schlieren (bottom) impacting spray images at different wall temperatures

The impinging spray images showed an intact liquid core coming from the nozzle and flowing along the surface of the wall. Its maximum elongation in radial direction, as function of the time from the impact, was called "liquid width" and we referred to it as the intact liquid core. The impinged spray height (thickness) is considered as the maximum height in the perpendicular direction with respect to the impinged wall, which is caused by impingement regimes of splash, rebound or the free spray flowing over the thin film. The thickness of the intact liquid on the plate has not a regular shape, we refer to its maximum height as to "liquid thickness". The liquid core is surrounded by an area composed of fuel vapour mixed to liquid ligaments and droplets more or less finely atomized. It extends itself on the plate beyond the "liquid width" and the "liquid thickness" and we refer to it as "vapor width" and "vapor thickness". Five consecutive events were acquired for each injection condition for an evaluation of the jets spread. The increment of the wall temperature has an effect on both the liquid, with much dispersed droplets, and vapour phases. It determines a shift of the impact regime from deposition towards rebound or thermal break-up, thus leading to enhanced vaporization. Looking at the schlieren spray images in figure 1, the mixed area, overhanging the liquid portion (dark part immediately on the wall), includes ligaments, droplets more or less finely atomized and vapor phase. The growth of this area appears evident when the temperature increases.

Figure 2 depicts the liquid (on the left) and vapour width (on the right) behaviour of the impacted fuel while changing the wall temperature from room to 573 K at the injection pressure of 20.0 MPa.

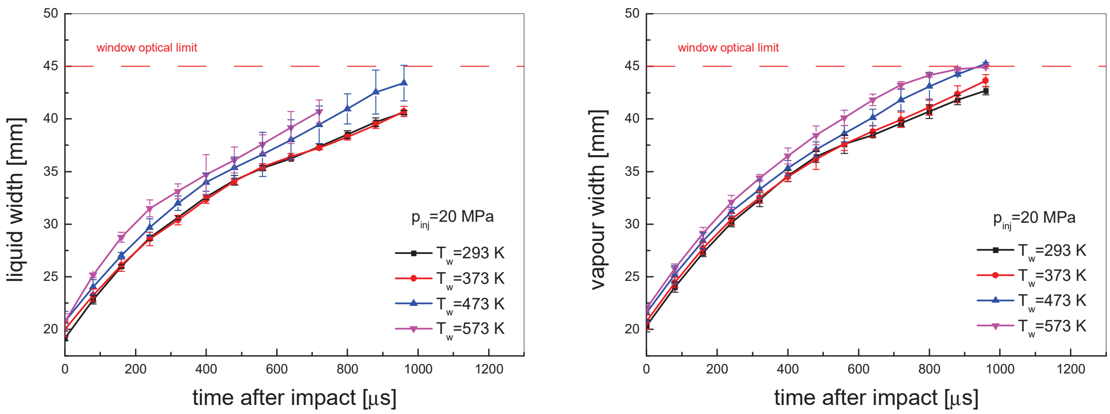

Figure 2. Liquid (left) and vapour (right) width at different wall temperatures

Both liquid and vapour profiles show a quasi-linear growth vs time for all the investigated wall temperatures. The increment of the wall temperature from 293 to 373 K doesn't produce any effect on liquid and vapour slipping in fact the curves (black and red respectively) overlap all along the injection duration. For temperatures higher than vaporization value of the iso-octane (372 K), the curves show a well-scaled trend of both liquid and vapour length with respect to the wall temperature, the higher is the temperature and the faster the fuel slipping results.

The curves reported in Figure 3 depict the behavior of the liquid (left) and vapor thickness (right) rebounding from the wall surface as a function of the wall temperature at the same injection pressure of 20.0 MPa.

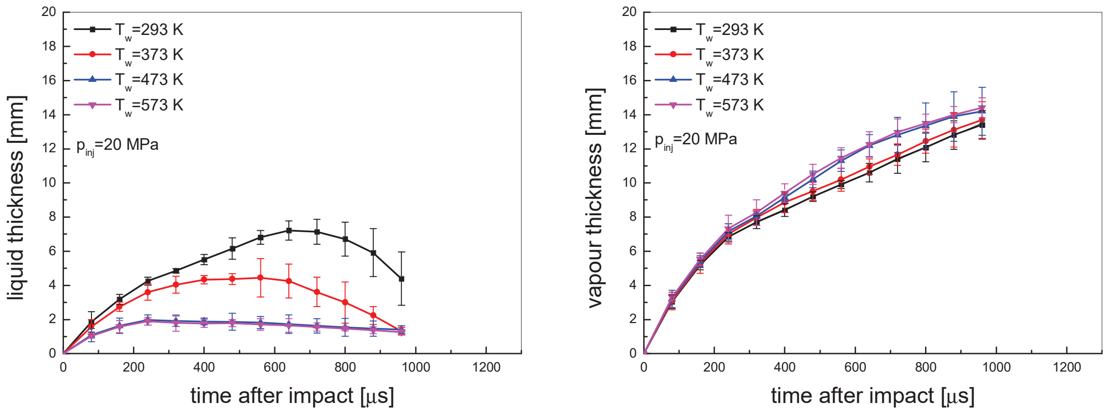

Figure 3. Liquid (left) and vapour (right) thickness at different wall temperatures

The increment of the temperature causes a reduction of the liquid thickness (on the left) and a growth of the vapour one (on the right). The thickness of the liquid phase shows an inverse trend with respect the wall temperature increase with a strongest rebound at room value (black line) and a quick tendency (at 473 and 573K) to saturate towards a stable value, around 2 mm, indicating a faster evaporation of the further incoming fuel. The behaviours of the vapour thickness curves are almost similar to the width ones (Figure 2) with a quasi-linear grow of the thickness up to the end of the injection process.

Finally, the effect of the injection pressure (ranging from 5.0 to 20.0) on both the liquid and the vapour phases after the impingement at the fixed wall temperature of 473 K was investigated. The injection duration was kept constant at 680 µs so the total amount of injected fuel increased with increasing of the injection pressure resulting equal to 5.0, 7.07, and 10.42 mg/stroke at 5.0, 10.0, and 20.0 MPa, respectively. Figure 4 reports the liquid (on the left) and vapour (on the right) width profiles as function of the injection pressure at the wall temperature of 473 K.

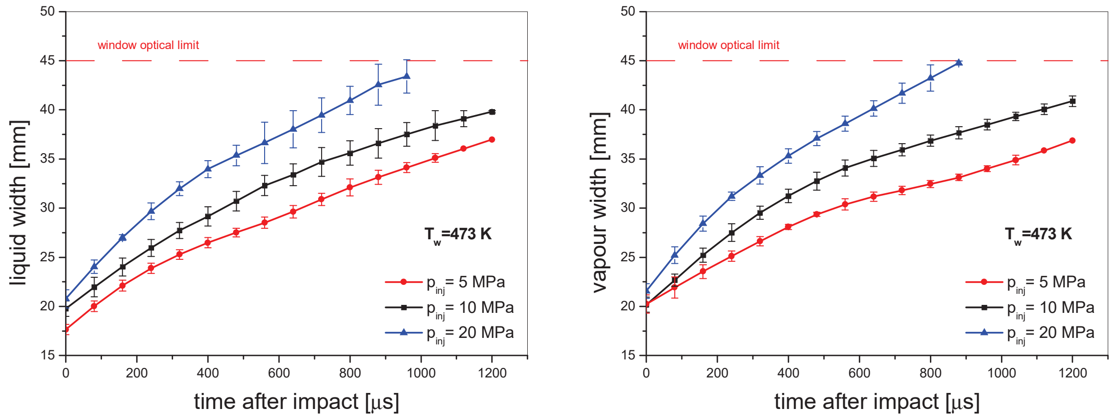

Figure 4. Effect of the injection pressure on liquid (left) and vapour (right) width at 473 K wall temperature

By increasing the injection pressure, the vapor phase increases prominently due to a finest atomization consequent the highest impact velocity and to an easier vaporization. The higher is the injection pressure, the longer is the width penetration because of the increased velocity (and the component parallel to the plate surface) of the impacting droplets. At impact completely developed, the gap between the curves slightly increases indicating a no-linear effect of the pressure on fuel slipping. Finally, the effect of the injection pressure was evaluated with respect to the thickness development, too. The results, here not reported for brevity, showed the vapour thickness increases with the increasing of the injection pressure while the liquid value remains stable around 2 mm and it is independent from the different injection pressures. More, liquid and vapour profiles begin to deviate each other just at the beginning of the impact, meaning that the existence of the vapour phase in addition to liquid one at 473 K as temperature of the wall is already present at the early stage of the impact and it is due to the vaporization process generated by the heat exchange with the plate.

Summary and Conclusions

Aim of this paper is a detailed understanding of the interaction and the heat exchange between injected fuel and heated wall under different engine-like conditions, studying both the liquid and the vapour phases as the wall temperature varied from room to 573 K. Iso-octane was injected in a constant volume vessel, where gas was kept constant at atmospheric back-pressure and the injection pressure varied in between 5.0, 10.0, and 20.0 MPa. Mie-scattering and schlieren images techniques were coupled in a quasi-simultaneous timing to obtain information of both the liquid and the gaseous phases. A homemade software for the processing of the spray images was used to extract the diffusion and evaporation parameters that characterize the impingement of the fuel.

The optical technique combined with the adopted image processing procedure were well suitable to capture the peculiarities of the diverse phases of the fuel and were sensitive to the governing parameters:

- temperature: a scaling behavior of the liquid and vapor width/thickness vs. the time from the start of the impact
- injection pressures: a proportional increasing of the fuel slipping both along the radial and vertical direction

Finally, the data could be used to initialize and validate the spray-wall interaction models and to support the combustion system developments.

References

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