Study of liquid and vapour phases of a GDI spray

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Abstract
Gasoline direct injection (GDI) systems have become dominant in passenger cars due to their flexibility in managing and advantages in the fuel economy. With the increasingly stringent emissions regulations and concurrent requirements for enhanced engine thermal efficiency, a comprehensive characterization of the fuel spray behavior has become essential. Characteristics of free and impingement spray fueled with iso-octane were investigated by a hybrid Mie scattering and schlieren optical technique with a direct injection gasoline injector, from the Engine Combustion Network (ECN). The experiments provided the spatial distribution and time-resolved evolution of the free, as well as the post-impingement spray characteristics under various operating conditions. A customized algorithm, able to catch the contours of both liquid and vapour/atomized phase, was used to extract the diffusion and evaporation parameters that characterized the fuel spray. Aim of this study is a detailed understanding of a GDI spray evolution under engine-like conditions, by studying both the liquid and the vapour phases as the ambient and injection conditions vary in a controlled environment.

Intoduction
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 degree of fuel atomization and vaporization but, at the same time, create an over-penetrating spray, so optimization is required [2]. Due to the short distance between the injector nozzle and the piston head/cylinder walls, one of the major drawbacks of the GDI systems is the impingement of liquid fuel on the combustion chamber wall that produces an increasing of HC emissions and soot

formation due to the fuel film deposits on the piston head. In this work, both free evolution and spray-wall interaction of a GDI spray were investigated at several operative conditions in a constant volume vessel by two synchronized optical techniques, schlieren for the vapour and Mie scattering for the liquid phase, working in alternative and quasi-simultaneous mode.

Experimental Methods

The tests were performed in a constant volume combustion vessel optically accessible by three quartz windows allowing the admittance to the investigated area. Iso-octane was fueled by a solenoid-activated eight-hole direct-injection gasoline injector from the Engine Combustion Network (ECN) effort on gasoline sprays (Spray G). More details on the adopted injector were reported in [3, 4]. 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 located in the rail. Both the injector and the fuel temperature were kept at 363 K. 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 by a 90 mm lens with f-stop 1-2.8. 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. Further specifications on the adopted hybrid optical setup as well as on the image processing procedure were reported in [5].

Results and Discussion

In the first part of the work will be studied the liquid and vapor envelopes of free sprays as function of the injection pressure, the ambient temperature, and the backpressure in the vessel, through the measurements of the axial penetration and cone angle. The changes in the spray structure and the vaporization processes for non- and flash-boiling multi-hole sprays were investigated over a broad range of ambient conditions using Mie scattering and schlieren optical techniques. The tests were carried out at the injection pressure (p_{inj}) of 10.0 MPa and five consecutive measures were acquired per each injection condition for an evaluation of the jet spreads. Fuel spray images were acquired at ambient temperatures (T_{amb}) ranging from 333 to 573 K. Four ambient pressures (N_2), corresponding to densities (ρ_{amb}) of 0.2, 0.5, 1.0, and 3.5 kg/m^3, were investigated for each ambient temperature. Figure 1 summarizes the conditions evaluated. At the fixed time of 720 μs from the start of injection, contours of the liquid and vapor phases of the spray, superimposed to the schlieren images, are shown. Each row reports a different ambient gas density while it is possible to evaluate the ambient temperature effect along the vertical direction. The inner (blue) contours were derived from the Mie scattering images and represent the liquid phase. The outer (red) contours were derived from the schlieren images and include the liquid core and vapor phase. The effect of the gas density is manifest: reduction of the axial penetration and a slight contraction of the spray cone angle. At the ambient temperature of 333 K, the vapor phase of the edge was slightly larger than that of the liquid phase, which suggests that the vaporization occurred along the perimeter of the spray plume. Flash boiling conditions (last column in Figure 1) occur when the ratio of the ambient to the saturation pressure is lower than 1. The individual spray plumes are observed to collapse toward the spray centerline with vortexes observed all along the spray edges. The spray collapses into a single solid-cone plume with a longer spray tip and a narrowed spray cone. The vapor quantity increases at higher rate with decreasing ambient /saturation pressure ratio during flash boiling conditions, due to a combination of prompt thermodynamic phase transition and an enhanced atomization process [6]. In addition, at reducing of the gas density, the liquid phase captured by Mie scattering is not as dense as that at the non-flash boiling conditions. For flare flash-boiling conditions, the distribution of liquid phase is more uniform and symmetric along the spray axis while the vapor boundary is mostly found in the lower part of the spray plume. Finally, at the highest ambient temperature (573 K), individual plumes are no longer discernible and a strong reduction of the liquid phase is detectable due to the quasi-complete vaporization of the injected mass.

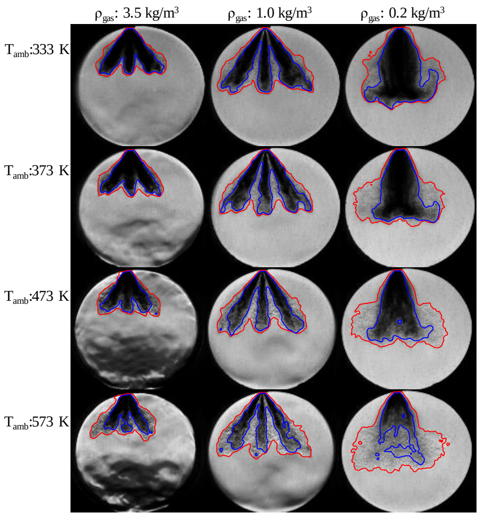

Figure 1. Liquid and vapor envelopes for different ambient conditions

Figure 2 depicts the schlieren axial penetration profiles versus the time after the injection for different gas densities, at the ambient temperature of 373 K. The penetration was extracted by selecting the farthest point of the spray contour along the axis of the nozzle. The profiles show a quite regular growth with the time and a well-scaled behavior with respect to the gas density. They decrease with increasing of the ambient pressure due to the increase of the resultant drag force. The lowest density case provides a higher penetration and thinner sprays. The reason of this is mainly attributed to the effects of flashing conditions that promote the development of spray collapse, which increase penetration and reduce the total spray angle.

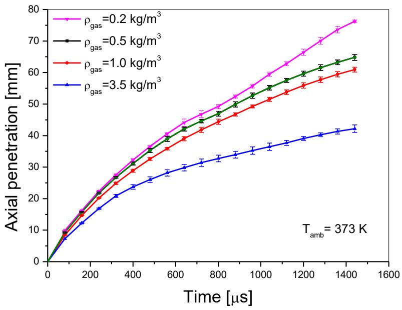

Figure 2. Effect of the gas density on the axial penetration

The spray characterization was completed by studying the interaction of the fuel with a heated flat wall under engine-like conditions, observing both the liquid and the vapour phases as the surface temperature varied (room to 573 K). 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 facing orthogonal to the injector axis. The same hybrid optical setup as well as the images processing procedure described before were used for investigating the liquid phase from Mie scattering images while the corresponding schlieren ones were employed to visualize the vapour phase. The test conditions for the spray-wall interaction experiments are listed in Table 1.

Table 1. Test conditions

Ambient gas temperature [K]	Ambient gas density [kg/m³]	Ambient gas composition	Ambient gas velocity [m/s]	Fuel injection pressure [MPa]	Fuel	Fuel temperature [K]	Energizing time [μs]	Distance between injector tip to impinging surface [mm]	Wall temperature [K]
293	1.12	100% N_2	0	5, 10, 20	Iso-octane	363	680	21	293, 373, 473, 573

Figure 3 reports an impacting spray sequence at different wall temperatures (from 293 to 573 K) from Mie scattering (on the top) and schlieren (on the bottom) optical technique. The imagines refer at the time step of 480 μs after the impact and 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 vapour from schlieren ones. 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. 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".

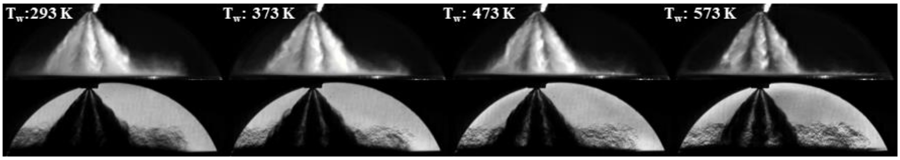

Figure 3. Impacting spray images for different wall temperatures

After the impingement, the fuel develops on the wall in regular and quasi-symmetrical mode on both sides with respect to the injector axis. Vortexes are formed at the jet periphery due to the interaction with the wall and the ambient gas. The slipping/rebounding fluid shows a double structure: denser and impenetrable to the schlieren light beam close to the wall, indicative of predominance of a dense liquid phase, lighter and almost transparent upper the plate, symptomatic of vapour generated by the heating with the wall. The increment of the wall temperature has an effect on both the liquid, with much dispersed droplets, and the vapour phases. It determines a shift of the impact regime from deposition towards rebound or thermal break-up, thus leading to enhanced vaporization. The growth of the mixed area, overhanging the liquid portion (dark part immediately on the wall), appears evident when the temperature increases. More, the higher is the temperature of the wall the stronger the characteristic vortexes of the vapor phase appear. The fuel vaporization is encouraged mainly by two factors: the impact that contributes to the breaking of the droplets thus facilitating the evaporation process and the heat transferred to the droplets from the wall giving a contribution to the latent heat of vaporization and determining the secondary evaporation of the droplets. As consequence of the vaporization process, a strong reduction of the liquid thickness comes out by looking at the Mie scattering images when increasing the wall temperature from room value to 573 K. Figure 4 depicts the liquid width (on the left) and thickness (on the right) profiles versus time as function of different wall temperatures at injection pressure of 20.0 MPa.

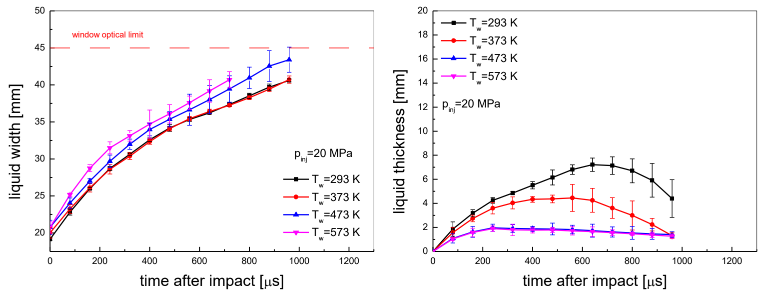

Figure 4. Liquid width and thickness profiles at different wall temperatures

The increment of the wall temperature from 293 to 373 K doesn’t produce any effect on liquid width in fact the curves (black and red respectively) overlap for all the entire injection process. For temperatures higher than vaporization value of the iso-octane (372 K), the curves show a well-scaled trend of liquid length with respect the wall temperature, the higher is the temperature and the faster the fuel slipping results. Vice versa, the liquid thickness shows an inverse trend with respect the wall temperature with a strongest rebound at room value (black line). At wall temperatures of 473 and 573 K the trend is still of increasing versus the time from the impact only up to 200 μs with a quick tendency to saturate towards a stable value, around 2 mm, indicating a faster fuel evaporation.

Conclusions

Mie-scattering and schlieren images techniques were coupled in a quasi-simultaneous timing for studying both the liquid and the vapour phases from a multi-hole GDI injector. The experiments provided the spatial distribution and time-resolved evolution of the free, as well as the post-impingement spray characteristics under various operating conditions. The effects of both ambient temperature and density were evaluated on the free spray morphology under conventional and flashing conditions. More, the spray-wall interaction was studied and the separate behaviour of both liquid and vapour phases was investigated as function of different wall temperatures. The combined optical technique has proven to be well suitable to capture the peculiarities of the diverse thermodynamic phases of the fuel and sensitive to the governing parameters. Finally, the data generated will be used to support the validation of spray-wall interaction models and to support the combustion system developments. For future works, wall-film characteristics, wall temperature and heat flux measurements in the spray-wall test will be further investigated.

References

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