GASOLINE SPRAY CHARACTERIZATION AND DROPLETS-WALL INTERACTION AT DIFFERENT PISTON TEMPERATURES

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Abstract
Spray/wall interaction has a significantly influence on the mixture formation process in gasoline direct injection (GDI) engines. Moreover, the fuel wall film and the resulting delayed evaporation of the liquid fuel are the main sources of soot formation in the internal combustion engines. In this paper, the spray evolution from a multi-hole GDI injector was investigated into an optical accessible vessel and environmental controlled through optical diagnostic developed under different injection strategies varying the duration and pressure of injection. In particular, a set of measurements were performed to characterize the spray evolution and the spray impact at different wall temperature. 2D high temporal and spatial resolution images of fuel spray were collected to obtain information about the penetration length, and wall impact hence about mixture formation process. Firstly, the spray evolution was analysed through the measurement of penetration length by visible high speed camera; secondly, the impact on the wall piston was analysed by means infrared thermography. The results obtained highlight the influence of injection pressures on the penetration length and the importance of piston temperature during the spray/wall impact.

Introduction
In order to respect the new emission limits imposed by internal combustion engines, in terms of significant reductions of NOx and HC and limitations to carbon monoxide and soot, the continuous research of thermodynamics processes occurring in the cylinder is a priority [1,2]. Certainly, the emission reductions pass through an efficient combustion. Thus, to modify technically the original layout [1,2] of the internal combustion engines, the automotive industry are moving. A deep knowledge of the process of mixing air/fuel through the characterization of the structure and evolution of the spray and their interaction with the flow field of air and solid surfaces is primary for the energetic optimization of the combustion processes.
Therefore, the analysis of the parameters which influence the structure and the spatial-temporal evolution of the spray is interesting [3]. Indeed, only a good injection can ensure a proper combustion in both modern compression and spark ignition engine for light duty vehicles [1,2]. Particularly, the control of the mixture formation process in the combustion chamber of GDI engine, is an objective of

great interest, since it would lead to the GDI engine optimization over the whole range of operating conditions [5].
The study of the physical relationship in the droplet/wall interaction is fundamental to understand the fuel evaporation process: an insufficient time for the fully evaporation of spray droplets, produces a liquid fuel impingement on the cylinder wall or piston surface, leaving deposits on the surface of the combustion chamber. This is a limitation of GDI engines. They have to be further optimized particularly in regard of PM (particulate matter) emissions. It is generally accepted that the deposition of liquid fuel wall films in the combustion chamber is a significant source of particulate formation in GDI engines. Particularly, the wall surface temperature and the temperature drop due to the interaction with liquid fuel spray were identified as important parameters influencing the spray-wall interaction [4].
A reason of a higher production of soot particle emissions is the wall film formation. It is therefore necessary to carry out investigations into the formation of wall film during the droplet impingement. On other hand, the mixture formation is guided by the piston top surface shape and piston temperature.
In this paper, the spray evolution from a multi-hole GDI injector was investigated into an optical accessible vessel and environmental controlled for different injection strategies varying the duration and pressure of injection. A set of measurements were performed to evaluate the spray evolution and the spray impact varying the wall temperature. 2D high temporal and spatial resolution images of fuel spray were detected in order to measure the penetration length, and the effect of wall impact. Moreover, the effect of different top surface piston temperature during the gasoline spray impact is analysed for different operating conditions.

Experimental Apparatus and Procedures

The basic evolution of a spray derived from a GDI injector and on its wall interaction on the piston top surface in optically-accessible vessel at atmospheric pressure and ambient temperature was investigated. The experimental set-up employed consists of the following modules: a wall guided injection system, an aluminium GDI commercial engine shaped piston, a data acquisition and a control units, and an optical apparatus made of a high luminosity 1000 Watt halogen lamp an Infrared Camera and a Visible Fast Camera.
Two set of tests were carried out as shown in Table 1: the first was made varying the injection pressure at fixed piston temperature and Duration Of Injection (DOI), the second was made varying the piston temperature for different values of DOI and injection pressure. The total amount of the injected fuel for all the investigated conditions is also reported in the Table 1.

Table 1. Operating condition investigated.

DOI [µs]	P_{inj} [bar]	Tp [°C]	Q [mg/stroke]
1666	**30-50-100-120**	25	10,4-11,1-15,1-16,1
2220	100	**25-130-180-230**	20,2
3040	50	**25-130-180-230**	19,8

In Figure 1 is reported the optical apparatus, the injector was fixed by -60 degrees, with respect to the vertical axis of the piston. This allows the orientation of the nozzle in the same way of the commercial engine.
The piston was heated at different piston temperatures using a heating band wrapped around the piston. The temperature was monitored by 7 thermocouples positioned on the piston (Figure 1). A synchronized pulse from the ECU started the spray command, the lamp and the camera CMOS Fastcam Photron SAX2 for capturing images of the evolving fuel or FLIR Infrared camera for the piston temperature analysis.

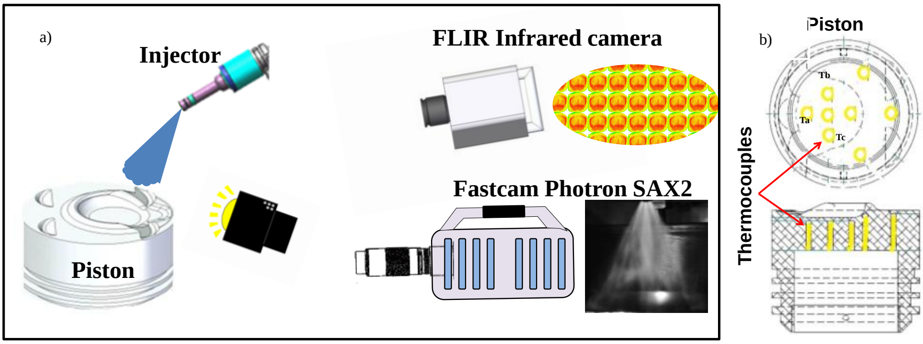

Figure 1. a) Experimental setup for optical investigations of the spray evolution, b) thermocouples position on the piston surface.

Result and discussion

During the injection phase, the images acquired by means of the IR camera allowed to obtain the field of piston surface temperature near the location of thermocouples. Different tests were carried out varying the piston temperature and the injection pressure. The wall piston temperature values are fixed at 130, 180, and 230°C. As an example, Figure 2 reports some images detected by the IR Camera at the injection pressure of 100 bar and DOI=2220µs and the average piston heating temperature of 230°C.

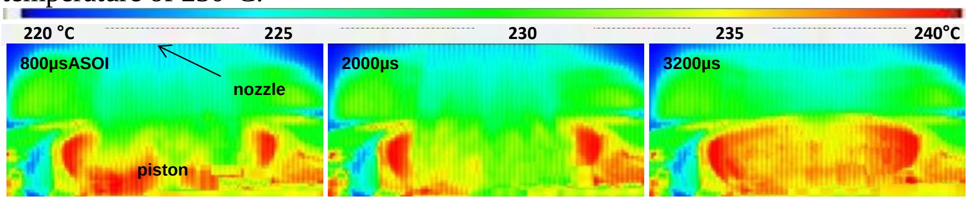

Figure 2. Sequence of images obtained by IR camera at 800, 2000 and 3200 µs at the injection pressures of 100 bar, DOI=2220µs and piston temperature of 230°C.

For every analysed image, the temperature distribution is not homogeneous on the piston surface. This is a consequence of the thermal exchange between the hot air near the heated wall piston. The piston temperature value changes when the fuel impact on its top surface. Finally, at end of acquisition when fuel injection ends, the temperature of piston doesn’t reach the starting value. The cooling of the piston surface worst the impinged fuel evaporation and probably it causes an increase of soot emission.

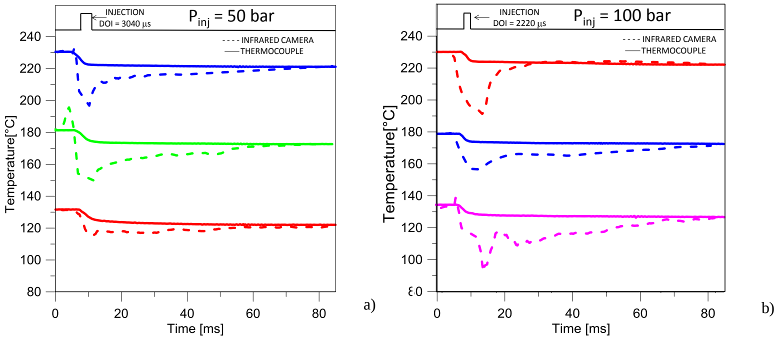

Figure 3. Piston temperature detected by thermocouples and IR camera for two different injection pressure a)Pinj = 50 bar and b) Pinj = 100 bar.

The temperature measurements obtained from infrared analysis were compared to the temperature values detected by the thermocouples. Figure 3a and 3b show the results at injection pressure of 50 bar and 100 bar, respectively. A better information is obtained by the infrared analysis with respect to the temperature acquired with the thermocouples system. The infrared images show that the piston surface temperature drops to lower values and then grow thanks to the heat exchange with the inner and hotter layers of piston. This effect is similar for all piston temperatures and for the two different injection pressures.

Imaging of the injection phase was performed using the setup depicted in Figure 1. The spray was illuminated using a lamp from the bottom in order to achieve homogeneous illumination of the injection event for the selected exposition time. The spray images were taken with the field of view shown in Figure 1 using the fast camera. This allowed evaluation of the spray properties such as the penetration of the jets and their eventual impact on the bowl, the atomization of the spray and the vaporization after the impact. A set of experiments were carried out to obtain a database of spray development data which are essential for developing the knowledge of the underlying mechanisms responsible for atomization under realistic engine conditions. By means of the Fast Camera it was possible to acquire the spray evolution during injection phase and subsequently after the impact on the wall piston with a time step of acquisition of 100µs. The spray was recorded at a frame rate of 10000 frames per second. The spatial resolution was of 0.108 mm per pixel. The spray evolution using commercial gasoline is reported in Figure 4. Four different injection pressure values were considered: 30, 50, 100 and 120 bar fixing the DOI at 1666µs. In order to take into account the cyclic variability the measurement were performed considering ten cycles for each test condition. Figure 4b shows the fuel penetration for different injection pressures condition, at ambient temperature with a DOI=1666µs.

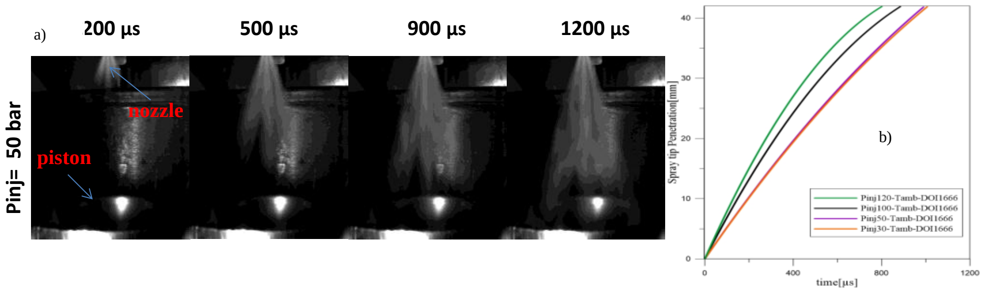

Figure 4. a) Sequences of the spray evolution for 50bar and DOI=1666 µs at different instant ASOI b) Spray penetrations.

The plot underlines an increase of the fuel penetration length with the rise of the injection pressure.

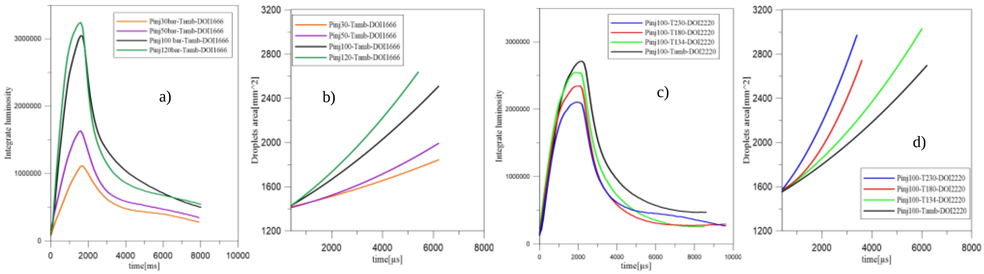

Figure 5. a) c) Integrate luminosity b) d) Droplets area for different test condition.

Figure 5a shows the trend of the integrated luminosity that is measured as the sum of the values of the pixels in the image of the spray without the background. This measurement is related to the liquid phase of the spray. At higher injection pressures the integrate luminosity increases. This is due to the greater amount of fluid injected into the time at higher value of injection pressure and to the higher atomization of the spray caused by the pressure rise. The spray evolution could be described by two different stages. First, the value of luminosity increases during the injection phase due to the higher light scattering produced by the fuel just injected**.** Second, after the end of injection, the image brightness decreases because of fuel evaporation. In Figure 5c at fixed injection pressure it can be observed that as the wall piston temperature increases, the integrated luminosity decreases. This effect is due to the higher temperature that allows the increasing of fuel evaporation and thus the reduction of the liquid phase. To underline the influence of piston wall temperature on the fuel evaporation, another investigation was made analysing the evolution of fuel droplets after the impact on the piston. Figure 5b shows the trend of this analysis for different injection pressures, at ambient temperature and with DOI=1666µs. The area increases with the pressure rise and the curve reaches the maximum value for injection pressure of 120 bar. A higher value of pressure produces a better atomization of the fuel. One of the reasons of this phenomenon is the higher rebound of liquid fuel droplets, when the injection pressure increases. Figure 5d shows that the piston wall temperature also influences the spray area. In particular, the temperature increase causes a curve inclination rise. This is probably due to the Leidenfrost effect that causes an increase of rebounded droplets at the increase of piston temperature.

Conclusions

The spray evolution from a multi-hole GDI injector was investigated into an optical accessible vessel for different injection strategies varying the duration and pressure of injection and the piston temperature. The main results can be summarized as:

- a fuel penetration for the un-perturbed non-vaporizing jets registered highest values for higher injection pressure;
- IR images show a lower piston temperature during the injection with respect to the thermocouple measurement.
- Visible images show that the increase of temperature produces a decrease of the fuel liquid phase during the injection. Instead the value of rebounded droplets is higher probably due to the LeidenFrost effect.
- high injection pressures and piston temperature improve the evaporation of fuel and reduce the fuel film on the piston.

It is also evident that the role of piston temperature is fundamental in the vaporization of fuel, thus related to performances and emissions of engine**.**

The use of combined measurements in a real engine and a closed vessel may improve and complete the knowledge of these complex phenomena.

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