SPRAY IMPINGEMENT ON A FLAT PLATE UNDER CROSS FLOW CONDITIONS

Panão M. R.* and Moreira A. L. N.*
moreira@dem.ist.utl.pt
***Instituto Superior Técnico**

ABSTRACT

The characteristics of the spray, as well as the interaction between the spray and the surrounding air, are important to achieve the benefits of the GDI concept. Although many research studies are reported which consider the structure of individual sprays, only a few regard the spray/wall interaction in the presence of air motion, as it appears in practical engines. This is the main goal of our study. In the first step, an experimental facility was built to study spray impingement on a flat plate under cross-flow conditions. This paper reports on the characterization of the injector in quiescent surroundings with a phase-Doppler anemometer system, on the visualization of spray impingement, using a combination of Mie scattering and shadowgraph to distinguish the liquid from the vapor phase. The results are analyzed in terms of the effect of the injection pressure and duration for different cross-flow velocities.

INTRODUCTION

Gasoline Direct Injection (GDI) technology is becoming increasingly popular due to its potential to reduce fuel consumption and to increase engine performance. This technology is classified in three types: the wall-guided; the air-guided; and the spray-guided (or air-assisted). In all types, spray impingement is one of the processes that contribute negatively to the fuel/air mixture preparation.

Despite the interest of understanding the fluid-dynamics of sprays impinging onto walls in the presence of a cross flow, for the development of practical engines, either GDI or PFI, only a few studies have been reported on the interaction between the spray and an air stream in experiments with well defined boundary conditions. Arcoumanis and Cutter [1] studied the spray/wall interaction in small direct-injection Diesel engines where the air motion was simulated by a steady cross-flow acting upon a transient Diesel spray. The authors showed that the mechanism of secondary atomization of the impinging droplets was altered as droplets from the approaching spray were entrained by the cross-flow. From the reported measurements of droplet size and velocities it can be inferred that the cross-flow deflects the spray and reduces its width due to the action of drag forces and shifts the impingement region downstream. As a result, droplets reaching the wall have a much higher diameter and velocity than they would have in the absence of cross-flow.

A similar study was performed by Arcoumanis *et al.* [2] but using a PFI injector directed at an angle of 20º and isooctane as the fluid. The authors observed similar structures in the wall-jet as in the D.I. Diesel spray. Measurements of droplet size and velocity confirmed the suggestion of Özdemir and Whitelaw [3], that the size of secondary atomized droplets increase with increasing film thickness. The authors also argue that a reduction of the cross-flow velocity and an increase of the fuel flow rate would increase the mean film thickness.

In the present work, although the main goal of our study is aimed at a GDI application, an experimental rig was built that allows to accommodate, both a GDI, as a PFI injection system. The work reported in this paper is the result of a first step aimed at building a fundamental basis on the influence of the pressure of injection (P_{inj}) and duration of injection (Δt_{inj}) for different cross-flow velocities on droplet size and velocity. To accomplish with that and for easy of experimental analysis, a PFI injector was used. The properties of the injector are determined based on the characterization of the spray in quiescent surroundings with a phase Doppler anemometer. The spray/wall interaction is studied based on a visualization technique, which combines Mie scattering with shadowgraph to identify both the liquid and the vapor phases and making use of a high speed CCD camera.

EXPERIMENTAL SETUP AND INSTRUMENTATION

The spray from a commercial injector used on PFI gasoline engines (BOSCH 280 150 726) is injected into a cross stream of air at atmospheric pressure and temperature flowing in a duct with a rectangular cross section 150x50 (WxH mm^2). The fuel spray impinges upon the bottom wall of the duct at a distance of 50mm from the tip of the injector, onto a plate of aluminium with a length of 270 mm. The side walls of the duct are made of glass to provide optical access for flow visualization and other optical techniques of diagnostic.

Gasoline is used as the working fluid (density 787 kg/m^3, kinematic viscosity 5.89x10^{-7} m^2/s and refractive index of 1.46) as there is sufficient evidence to suggest that there are no inert test fluids that can simulate accurately the atomisation characteristics of this fuel (Pitcher and Winklhofer [4]). A low-pressure Denso pump supplies the gasoline through a *monorail* to the injector located at the centre of the duct.

Fuel injection is triggered by a TTL pulse from an injector control driver controlled with a function generator computer board, NI 5411 from National Instruments, which allows control of the duration and of the frequency of injection independently. The injection pressure is controlled by a fuel-pressure regulator located downstream the injector. Calibration of the injector showed that the flow rate of fuel increases linearly with the duration of injection. Figure 1 shows a diagram of the experimental rig and Figure 2 shows a photo of the working section where impingement occurs.

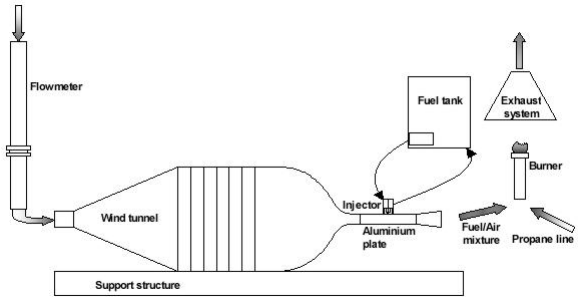


Figure 1 Schematic of the fuel injection rig

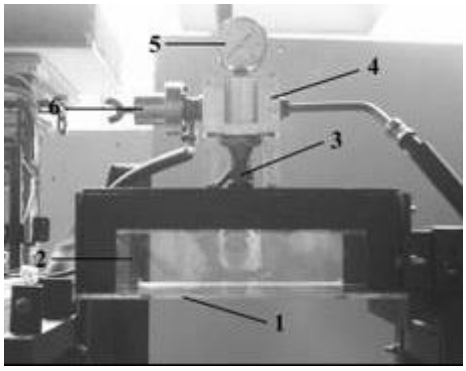


Figure 2 Low speed wind tunnel working section. 1) Impact surface; 2) Perspex or glass; 3) Injector; 4) Monorail; 5) Barometer; 6) Fuel-pressure regulator.

Macroscopic visualization of the flow is made by illuminating the flow with a laser light sheet (1 mm) obtained by spreading a 2 mm laser beam with a cylindrical lens. The beam is emitted by an argon-ion laser light source with a maximum power of 9W and the laser light sheet is collimated with a plane-convex lens with a focal distance of 400 mm. Images are recorded with a CCD Kodak SR-Series camera, triggered by a pulse signal synchronized with the injection system operating with a frame rate of 2000/s and with a spatial resolution of 256x120 (pixel^2) corresponding to a viewing area of 52x24 mm^2 (WxH) and an exposure time of 0.1 ms. For shadowgraph, the laser beam is expanded with a magnifying lens and collimated with a plano-convex lens with a focal distance of 235 mm. Figure 3 and Figure 4 show schematic diagrams of both visualization techniques.

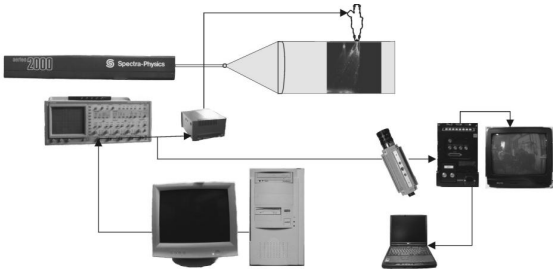


Figure 3 Schematic diagram of the optical system used for visualization through Mie Scattering

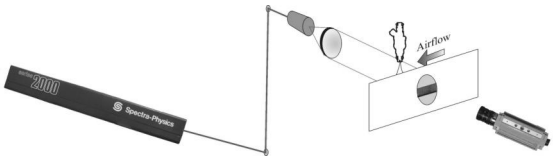


Figure 4 Shadowgraphy setup

The injector is characterized with a two-component phase-Doppler system from Dantec. The system consists of a 55X transmitting optics, a 57x10 PDA receiving optics and a Dantec 58N10 Covariance signal processor. The transmitting optics, in a standard two component form, include a Bragg cell with frequency shifting of 40MHz and a beam splitter to separate an Ar-Ion laser beam of 300 mW into wavelengths of 488 and 514.5 nm. In the transmitting optics the laser has a diameter of 1.35 mm, expander ratio of 1 and beam separation of 60 mm, originating a measurement volume diameter and fringe spacing of 150 μm, 2.671 mm (green) and 143 μm, 2.533 mm (blue), respectively. The number of fringes is 56 and the polarized light is parallel to the fringes.

The PDA receiving optics is oriented at a scattering angle of 30º, with a focal length of 500 mm and aperture of 0 mm, giving a maximum measurable diameter of 167.278 μm.

The Bandwidth used for both components was mostly 12 MHz (except for 4.5 bar where 36 MHz were used for the vertical component) and the gain was set to high. The signal to noise ratio was set to -3dB, the phase error to 10 degrees and the spherical deviation to 10%.

RESULTS AND DISCUSSION

Table 1 summarizes the working conditions considered throughout the paper. The cross-flow velocities were chosen so the interaction with the spray could be noticed (lower limit) and occurs within the length of the working section (upper limit). Transition of the boundary layer at the wall was forced at the beginning of the working section using a trip wire.

	Category	Values
Air stream	Air temperature T_{air}(ºC)	25 ºC (± 2ºC)
	Cross flow velocity V_c (m/s)	5.3, 11.5, 17.3
Spray	**Fuel**	**Unleaded Gasoline**
	Pressure of injection P_{inj} (bar)	2, 3, 4.5
	Duration of injection Δt_{inj} (ms)	3, 5, 7, 10, 20
Impinging surface	Impingement distance Z_w (mm)	50
	Angle of impact α_{impact} (º)	90

Table 1 Experimental conditions

Spray Characterization

The unconfined spray was first characterized based on phase Doppler measurements for pressures of injection of 2, 3 and 4.5 bar. The duration of injection was set at 10 ms and the frequency of injection to 10Hz, which is representative of a moderate speed in SI engines. In Figure 5 a set of four plots describes the spray pattern at 6, 8, 10 and 12 ms after the start of injection (ASOI), for an injection pressure of 3 bar. In each plot, the arrows represent the droplet velocity vector and the circles represent the Sauter Mean Diameter (SMD).

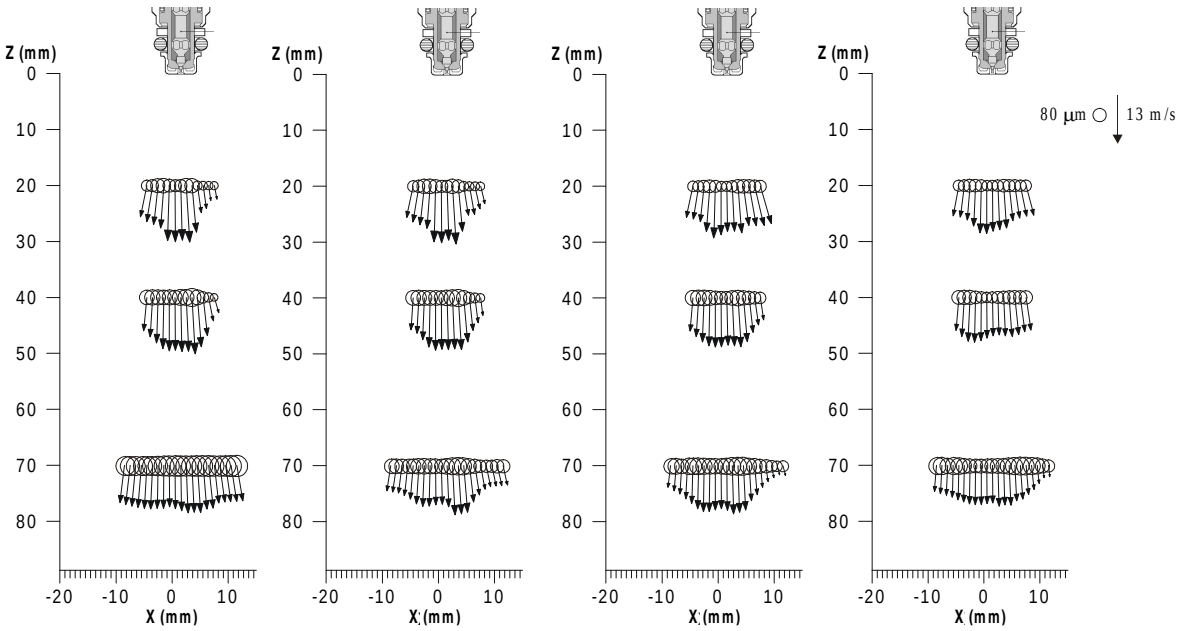


Figure 5 Spray characteristics for p_{inj} =3 bar at instants 6, 8, 10 and 12 ms after the start of injection (ASOI), respectively.

Measurements of droplet number density (not shown here, due to lack of space) showed a hump like profile near the nozzle exit, in accordance with the hollow cone structure of the spray. The hump like behaviour dissipates as droplets move downstream, due to the effects of dispersion and cross trajectories and, at x = 20 mm from the injector, the number density of droplets at the spray axis is already large enough to obtain statistically independent measurements of velocity and size. The first plot in Figure 5 was obtained at 6ms ASOI, which corresponds to the instant at which the droplets firstly injected arrive at a distance x = 70 mm below the injector nozzle. Maximum velocity values were measured at x = 20 mm downstream the nozzle, with values up to 18 m/s

at the centre, which decrease far downstream due to transfer of momentum with the surrounding quiescent air and attain values in the range 11 – 15 m/s at the far downstream station. Droplet size is rather uniform with values of SMD ranging from 50 to 90 μm at x = 20 mm, but increasing downstream up to 115 –128 μm at x = 70 mm..

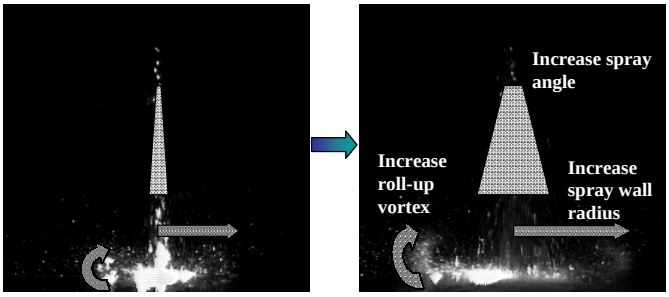
At later stages of injection, droplet size increases from the axis towards the periphery of the spray in accordance with the hollow cone structure, particularly at x = 40 mm below the nozzle because smaller droplets disperse faster towards the axis, where number density was initially smaller.

An important feature of the injector is due to the transient induced by the aperture of the injector. The reported measurements show that maximum droplet size occurs at the initial stage of injection at the far downstream axial station (t = 6 ms, x = 70 mm) which means that droplets firstly hitting the wall when impingement occurs are larger in comparison droplets injected at later stages. Therefore, the suggestion is that fuel initially injected has a larger contribution to the formation of a liquid film at the impinging surface. Closer of the injector does not seem to induce any peculiar behaviour.

The experiments included measurements for other pressures of injection (2, 4.5 bar besides 3 bar) and it was confirmed that an increase in the injection pressure reduces droplet size and increases droplet velocity.

Spray Impingement in Quiescent Conditions

The dynamics of impingement has been characterized based on flow visualization with Mie scattering combined with shadowgraph. Figure 6 shows the spray pattern in quiescent conditions, with a structure similar to that observed by Arcoumanis and Chang [5], Arcoumanis and Cutter [1] and Meingast *et al.* [6] with Diesel injectors and also by Arcoumanis *et al.* [2] with a gasoline injector.



(a – 2 bar) (b – 4.5bar)

Figure 6 Effect of the injection pressure upon spray structure and impingement characteristics 6ms ASOI

The results also show the formation of two roll-up vortices at the spray wall-jet after impingement. Increasing the pressure of injection also increases the spray angle, due to a higher differential pressure expanding the spray at the exit; increases the spray wall radius, as defined in the numerical model developed by Bai and Gosman [7]; and increases intensity and diameter of the roll-up vortices.

Also, secondary atomisation occurs as reported in Arcoumanis and Cutter [1], Arcoumanis *et al.* [2] and Özdemir and Whitelaw [3], due to splashing and rebound of the incoming droplets, as well as film stripping.

Effect of Pressure of Injection in Spray Impingement under Cross-Flow Conditions

Figure 7 shows the behaviour of the impinging spray in the presence of a cross-flow with an average velocity of 5.3 m/s for different values of the pressure of injection, as seen in Mie scattering images and shadowgraphs. Superimposed to the images are the axis of the injector and the wall boundary layer, for easy of analysis.

When the fuel is injected in the presence of cross-flow, a transverse drag force acts upon droplets and the spray is deflected, moving the impingement region downstream and reducing the influence of the roll-up vortices of the wall-jet. For the cross-flow velocity considered in Figure 7, two stagnation points are identified, the former at the impingement point of the incoming spray, the second as a result of the deceleration exerted by the cross-flow upon the liquid film spreading in the opposite direction.

The dark areas in the shadowgraphs correspond to the liquid phase and the dimples indicate the presence of vapour of gasoline. For the images at 3 bar and at 5 ms ASOI, the vapour phase appears with the incoming spray and is convected by the air stream. Also, a surface vapour layer appears which released from the impinging surface due to vaporization, either of the liquid film or of secondary atomised droplets. The interface between both is referred as the vapour shear layer. Comparison of the images at 7 ms ASOI for each injection pressure, suggest that the surface vapour layer increases with the injection pressure probably due to the enhancement of secondary atomisation, or to a increase of thickness of the liquid film, or even due to both effects. Senda *et al.* [8] showed that increasing the quantity of fuel impinging on the surface, more fuel adheres to it, increasing the

thickness of the liquid film and which sustains the idea of a higher surface vapour layer for a higher injection pressure, since more fuel is injected.

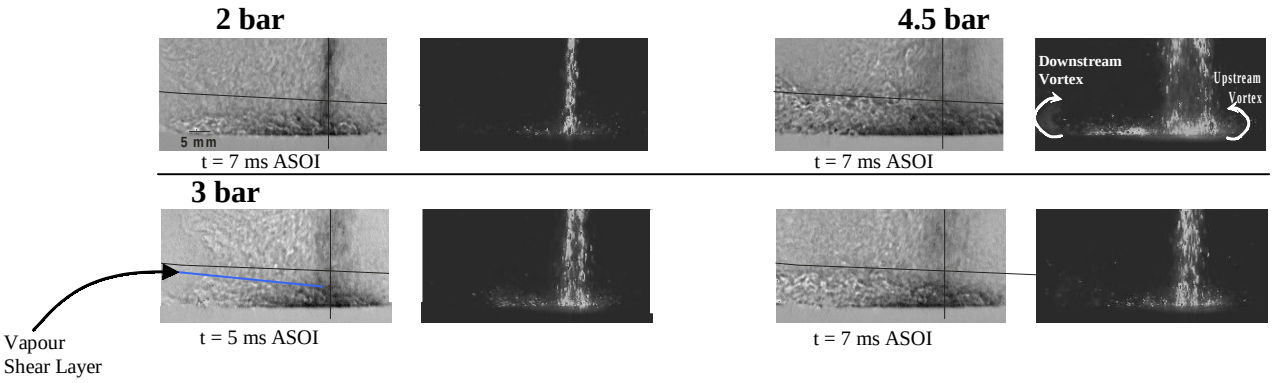


Figure 7 Mie scattering and Shadowgraph images of the liquid and vapor phase post-impingement with a cross-flow velocity of 5.3 m/s. Duration and frequency of injection of 10 ms and 10 Hz, respectively.

For larger cross-flow velocities (11.5 and 17.3 m/s), the deflection of the spray and the shift of the impingement point are more pronounced. The surface vapour layer appears to develop below the turbulent boundary layer, as shown in Figure 8.

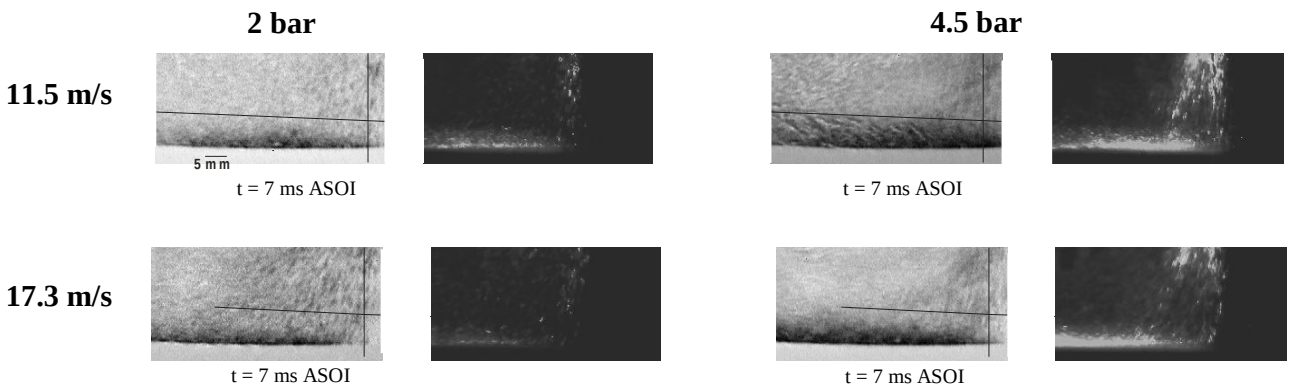


Figure 8 Effect of injection pressure and cross-flow velocity in the spray impingement.

An increase in the cross-flow velocity also reduces the influence of the roll-up vortices. In these images, the boundary layer seems to have a greater effect on the flow pattern, which is more visible at 7 ms ASOI, with p_{inj}=4.5 bar and V_c = 11.5 m/s. However, the magnitude of the influence of the cross-flow velocity on the spray structure reduces as the injection pressure increases, which is in accordance to what was verified for the unconfined spray, for which higher injection pressures produce droplets with larger velocities, reducing the influence of the air stream upon them.

Effect of Duration of Injection in Spray Impingement under Cross-Flow Conditions

Figure 9 shows shadowgraphs obtained at the last instant for several periods of injection. In accordance with the results of Senda *et al.* [8], the results suggest that the amount of fuel adhered to the wall increases with duration of injection. Also, the images seem to confirm the previous suggestion that an increase of the height of the surface vapour layer might be due to an increase of fuel thickness and/or to enhancement of secondary atomisation.

The magnitude of the Saffman lift forces upon the rolling droplets in the near-wall region where shear is larger and therefore render them significant relative to drag, e.g., Bai, [9] and fuel volatility may affect fuel/air mixing (e.g., Tong *et al.* [10]). Therefore, the surface vapour layer growth suggests that these phenomena, associated with the mixing capabilities of the turbulent boundary layer, may influence the fuel/air mixture preparation in cold-start conditions.

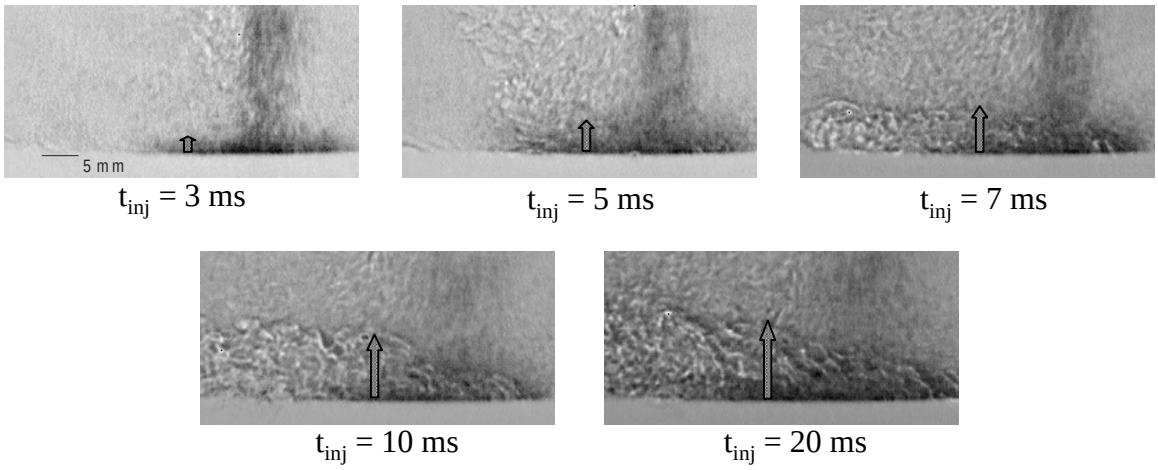


Figure 9 Effect of the duration of injection for 3 bar and cross-flow velocity of 5.3 m/s.

SUMMARY

This paper reports on the characteristics of a gasoline spray impinging upon a flat surface under cross-flow conditions. The study includes characterisation of the free spray in quiescent surroundings with a phase Doppler anemometer and analysis of the behaviour of impingement with a combination of Mie scattering and shadowgraph to distinguish the liquid from the vapour phases. The duration of fuel injection, pressure of injection and cross-flow velocity were varied to allow the study of the impingement under different conditions

Results showed the expected increase in the angle of the hollow-cone spray with increasing injection pressure; the formation of two roll-up vortices with and without cross-flow, in spite their influence was reduced when the air stream velocity is increased; the presence of two stagnation points in the impingement region and upstream. Analysis of the results further suggest a relation between the film thickness and the surface vapour layer, associated with the mixing capabilities of a turbulent boundary layer, may influence the fuel/air mixture preparation. This also suggests further areas for future work

ACKNOWLEGMENTS

The authors acknowledge the contribution of the National Foundation of Science and Technology of the Ministry for Science and Technology by supporting this study through the project POCTI/ EME/ 38082/2001 and by supporting M. R. Panão with a Research Grant.

REFERENCES

[1] Arcoumanis, C. and Cutter, P., "Flow and Heat Transfer Characteristics of Impinging Diesel Sprays Under Cross-Flow Conditions", *SAE Paper* 950448, (1995).

[2] Arcoumanis, C., Whitelaw, D.S. and Whitelaw, J.H., "Gasoline Injection Against Surfaces and Films", *Atomization and Sprays*, vol. 7, pp. 437-456, (1997).

[3] Özdemir, I. B. and Whitelaw, J. H., "Impingement of an unsteady two-phase jet on unheated and heated flat plates", *J. Fluid Mech*., vol. 252, pp. 499-523, 1993.

[4] Pitcher, G. and Winklhofer, E., "Droplet Size and velocity Measurements in the spray of a Direct Injection Gasoline Injector", *ILASS – Europe* '98, Manchester 1998.

[5] Arcoumanis, C. and Chang, J.-C., "Heat transfer between a heated plate and an impinging transient diesel spray", *Experiments in Fluids*, vol. 16, pp. 105-119, (1993).

[6] Meingast, U., Staudt, M., Reichelt, L., Renz, U., Sommerhoff, F.-A., "Analysis of Spray/Wall Interaction Under Diesel Engine Conditions", *SAE Paper* 2000-01-0272, (2000).

[7] Bai, C., Gosman, A.D., "Development of Methodology for Spray Impingement Simulation", *SAE Paper* 950283, (1995).

[8] Senda, J., Ohnishi, M., Takahashi, T., Fujimoto, H., Utsunomiya, A., Wakatabe, M., "Measurement and Modeling on Wall Wetted Fuel Film Profile and Mixture Preparation in Intake Port of SI Engine", *SAE Paper* 1999-01-0798, (1999).

[9] Bai, C.X., "Modelling of spray impingement processes", PhD Thesis, University of London

[10] Tong, K., Quay, B.D., Zello, J.V., Santavicca, D.A., "Fuel Volatility Effects on Mixture Preparation and Performance in a GDI Engine During Cold Start", *SAE Paper* 2001-01-3650, (2001).