

# Velocity and Size Distributions of Fuel Droplets in the Cylinder of a Two-Valve Production SI Engine

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## ABSTRACT

The results of this paper add to knowledge of the characteristics of the droplets emerging from an inlet valve as a consequence of manifold injection and were obtained by phase-Doppler velocimetry for injection against a closed valve and against an open valve. The investigation was conducted in three phases which made use of a Plexiglas cylinder head with moving valves, a motored and a firing engine. The engine was operated at full load and at 1200 rpm. The results show close correspondence between the cold and hot flows in terms of droplet sizes, that a film of liquid forms with injection against a closed valve and that injection against an open valve leads to most of the fuel emerging into the cylinder with size characteristics similar to those of the spray.

## INTRODUCTION

The purpose of the investigation described here is to determine the consequences of manifold injection for the characteristics of the fuel as it emerges from the inlet valve and thereby provide a basis for further consideration of the fuel distribution as the crank angle corresponding to ignition is approached. At the same time, it is necessary to provide the information in sufficient detail to allow interpolation and extrapolation by empirical expressions or by the use of computer-based calculation methods based on the numerical solution of conservation equations in differential forms. The provision of measurements in operating engines is expensive of time and effort so that a combination of hardware including a Plexiglas model of a cylinder head with moving valves but without a piston and an engine was used with the larger number of results obtained from the simpler configuration and confirmed by measurements obtained from an engine under non-firing and firing conditions.

The use of steady-flow rigs has been investigated by several authors including those of references 1 and 2 with laser-Doppler velocimetry as the main means of

measurement and it has been shown that the results in the valve-curtain area and for a short distance downstream are similar to those in the first part of the intake stroke of an engine. References 3, 4 and 5 describe related measurements of droplet characteristics and that the use of Plexiglas components offers the advantage of access to the manifold to determine the consequences of impingement. Of course, these cold-flow experiments do not consider properly the consequences of the evaporation which may occur in a firing engine in which further experiments are required, though with less detail than would otherwise be the case.

The phenomenon of droplet break-up has been studied in many experiments including that of reference 6 and phenomenological models have been devised to represent port injection (7) but the processes are likely to be more complex than appreciated in these attempts. Several authors have attempted to describe atomisation phenomena in terms of disintegration of liquid sheets (8,9) and comparisons between experiments and calculations have been reported as a function of needle lift (10). There is considerable information of sprays in atmospheric air (11, 12, 13) and links between the spray and knowledge of single droplet break-up in terms of the Weber number as by (14). It can be conjectured, however, that the mechanisms which lead to the nature of the fuel at exit from the inlet valve are more complex with atomisation of the spray of greatest importance when the valve is open and the droplets are sufficiently small so that they follow the flow and avoid impingement on solid surfaces before emerging. In practice, and even with the open valve, it is likely that droplets will impinge on the wall of the manifold, the valve stem and the valve itself and that the consequences of this will depend on the timing of valve opening and impingement, on the characteristics of the spray and on the temperature of the various surfaces. Secondary atomisation processes have been investigated, for example in reference 15, and show that a considerable quantity of liquid fuel mass passes a solid object as large droplets as a consequence of the formation of a liquid film, even though the impingement process can result in the reduction of the

average size of some droplets. Other phenomena of this type have been hinted at in references 4 and 5.

The above arguments emphasize the need for information on the relationship of spray and geometry on one hand and on the properties of the liquid fuel which exits the valve on the other hand, and this is addressed in the remainder of this paper. The flow configurations are described in the following section together with the instrumentation and the results are presented and discussed in the two subsequent sections which deal respectively with those from the steady-flow facility and from the engine.

## FLOW CONFIGURATIONS AND INSTRUMENTATION

The engine described by the characteristics given in Table 1 was modified with a quartz insert to allow optical access for the phase-Doppler velocimeter and, for the purposes of this investigation, it was operated at a rotational speed of 1200 rpm, at nearly full load: 100 mbars under atmosphere, and with a pintle injector.

Engine type	four cylinders in line
Bore and stroke	86 x 86 mm
Displacement	1998 cc
Compression ratio	7.3 in motored case 8.8 in firing case
Mean piston speed	3.4 m/s at 1200 rpm
Valves per cylinder	2
Inlet valve diameter and lift	42.6 mm and 11.5 mm
Exhaust valve diameter and lift	34.5 mm and 12.2 mm
Seat angle	45 degrees
Valve timing	IVO at 1° B TDC IVC at 44° A TDC
Ignition timing	25° B TDC
Injection timing	open and closed valve

Table I: Characteristics of the two-valve SI engine

The arrangement of the test-bed allowed it to be driven by a motor or to operate in the usual firing condition. The engine was instrumented so as to measure the flow-rates of fuel and air, the rotational speed and various temperatures each as a function of crank angle. The emphasis of the present measurements is, however, on the measurements of droplet velocity and size by phase-Doppler velocimetry and this is reflected in the present description. The single cylinder arrangement used with the Plexiglas head from the above engine is shown in Figure 1. The head is geometrically identical to that of the engine and the injector is the same. The valves were operated by an engine camshaft to provide movement corresponding to the 1200 rpm engine speed, the injector was operated by the same engine management arrangement with the same timing and the downstream cylinder was connected to a pump which provided the flow of air. Preliminary measurements with a laser-Doppler velocimeter identified the region of dense spray to be the

narrow cone shown on Figure 1 and the detailed measurements of the next section were obtained at the location shown on the figure as a consequence. The phase-Doppler instrument used with Plexiglas head has been described by Bachalo et al (16, 17) and by Vannobel (18) and was applied after flow visualisation (4,5) and laser-Doppler velocimeter measurements had determined the regions of main interest. In particular, the measurements of droplet characteristics were obtained at discrete locations which were chosen to correspond to those where the arrangement of valve, port and cylinder wall had ensured that a large proportion of the air flow and droplets were present. The instrument used for the engine experiments was that described by Hardalupas, Taylor and Whitelaw (19). In both cases, the resulting measurements of droplet velocity can be expected to be more accurate than required by the deductions made from the results and the same can be said of the droplet diameters. No attempt has been made to measure the liquid flux though it can be inferred, albeit with considerable inaccuracy, from the data rate and droplet diameters of the results.

Gasoline was used as fuel in the Plexiglas head and iso-octane in the engine because it allowed optical access for longer periods without fouling of windows. It should be remembered that the evaporation characteristics of iso-octane are different from gasoline. The injector was the same and in the same location for the two investigations.

## RESULTS FROM PLEXIGLAS HEAD WITH RUNNING CAMSHAFT

The manifold was arranged to operate with a pressure depression between 20 and 100 mbars as in the engine and Figure 2 shows the relative data rates and velocities of droplets emerging from the inlet valve as a function of crank angle where, at the rotational speed, one degree corresponds to approximately 0.1 ms. The two parts of the figure correspond to closed and open valve injection and are accumulations of data over several cycles.

With injection against a closed valve, the liquid accumulates on surfaces and presumably mainly on the valve until opening occurs after which the decreasing velocity associated with the opening valve causes the variation of velocity with crank angle. The first droplets, and there are few and of low velocity, were swept from the valve surface by the low air velocities close to the surface and were shown to be of comparatively large diameter, with Sauter Mean Diameter greater than 50 microns. The main part of the spray arrived at the measuring location after valve closure with a transit time from the valve of more than 6 ms and continued for approximately the 46 degrees of open valve (4.6 ms). The later droplets may have been slower moving and larger as they were swept from liquid films on surfaces within the port, or droplets which had been transported from another part of the cylinder.

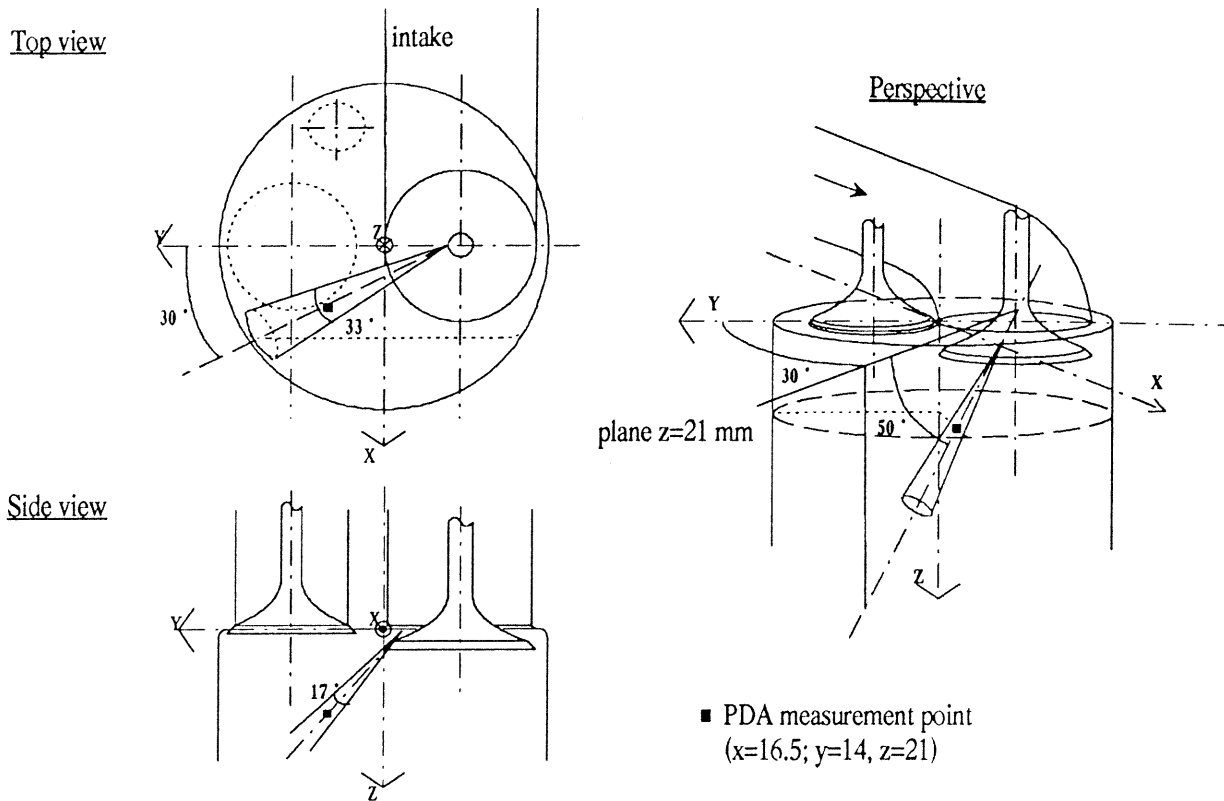


Figure 1: Location of the dense spray cone inside the transparent cylinder downstream of the Plexiglas model cylinder-head.

The results for open valve injection have a similar trend but a two-part structure is apparent with the first corresponding to droplets swept into the cylinder without striking surfaces and followed by droplets which have impinged on surfaces sometimes to undergo secondary atomisation and on others to form films which are stripped by the near-wall boundary-layer flow. The measured Arithmetic Mean Diameter of the spray was around 30  $\mu\text{m}$  and this value was also measured for the first droplets of figure 2.b in contrast to the second wave of droplets which had an AMD in excess of 45  $\mu\text{m}$  and with some droplets considerably larger than 100 microns.

Experiments were also performed with injection on alternate cycles every two or four cycles; the results showed that liquid fuel remained in the port from one cycle to another with injection against a closed valve and did not with the open valve.

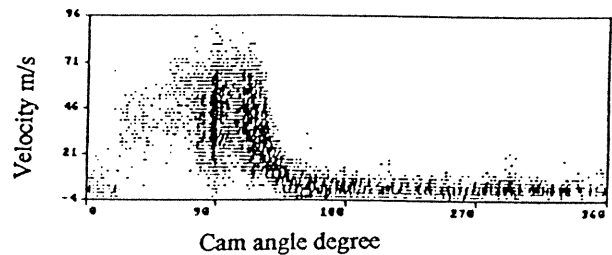


Fig.2.b) Injection against an open inlet valve

Figure 2: Droplet velocities with injection over 18 degrees against a closed inlet valve (Fig.2.a) and against an open inlet valve (Fig.2b).

It can be anticipated that this fuel would evaporate in a hot engine as would any fuel injected long before valve opening, and would contribute to the provision of a homogeneous mixture.

RESULTS FROM ENGINE

Measurements were made in the engine under motored and firing conditions and results are shown on Figures 3 for these two situations with the motored arrangement clearly giving rise to a greater proportion of small droplets in this case of injection against a closed valve. Thus, we can expect that the small droplets have evaporated preferentially in the hot engine. The detailed measurements

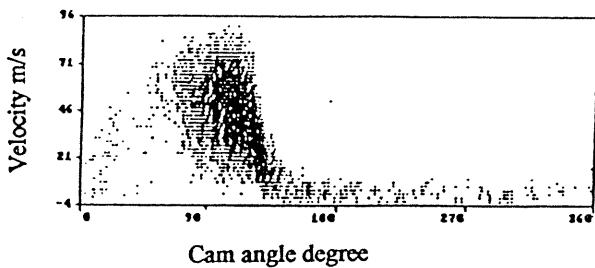


Fig.2.a) Injection against a closed inlet valve

upon which these histograms are based also showed the much higher data rates associated with the motored engine.

The variation of droplet concentration was examined in the vicinity of the measuring location selected on the basis of the flow from the Plexiglas model and the results showed a reduction from the maximum data rate at the selected position to half this value at location 50 mm on either side.

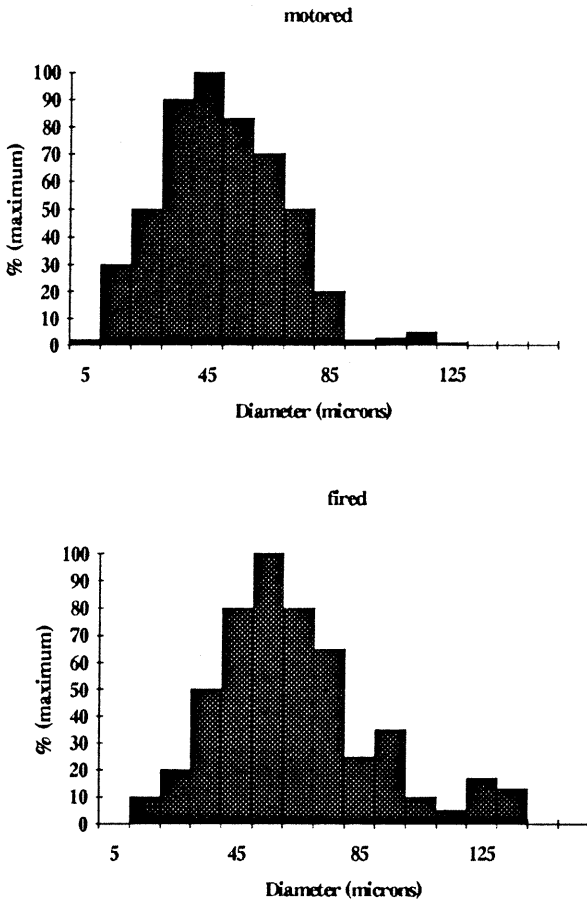


Figure 3: Histograms of droplets size for motored and firing operation at 1200 rpm and manifold depression 200 mbars; SMDs correspond to 35 and 70 microns respectively.

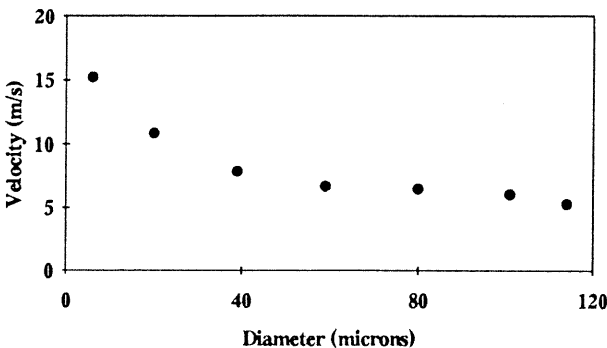


Figure 4: Variation of velocity with droplet size for injection against a closed valve in the firing engine.

A typical measurement of velocity as a function of droplet size is shown in figure 4 with the small droplets having velocities up to twice those of the larger droplets. This result again corresponds to injection against a closed valve and suggests that the smaller droplets are carried with the bulk velocity of the air whereas the larger droplets, which are considerable larger than those produced by the spray, are generated from liquid films on surfaced and removed by a form of secondary atomisation at the lower air velocities close to these surfaces.

Figure 5 also allows comparison between data rates, droplet sizes and diameters in the firing engine with injection against a closed and an open valve. It is evident, as we expect, that injection against a closed valve gives rise to a wider range of droplet sizes. In this case, the time between injection and valve opening was comparatively short so that there are many droplets and it can be conjuctured that a longer time interval would decrease this number perhaps to zero. With injection against an open valve, the period over which droplets are present is longer than the injection duration by some 10 crank angle degrees due to slow-moving droplets close to walls in the port and valve curtain.

### CONCLUSIONS

The main conclusions from the experiments described above may be summarised as follows.

1. The droplets emanating from the inlet valve do so with a high proportion of the liquid flux contained in a cone of comparatively narrow angle.
2. The results from the Plexiglas model show that injection against an open valve results in two waves of droplets with the first closely related to the characteristics of the spray and the second modified by secondary atomisation due to impingement and to stripping of liquid films. Corresponding results with injection against a closed valve show a larger Sauter Mean Diameter due to much of the fuel existing as liquid films and its removal as larger and slower moving droplets by the boundary-layer flows in the port and valve gap.
3. Similar measurements in the engine, driven by a motor, were consistent with those in the model.
4. The firing engine involved high temperatures and these, in turn, led to evaporation of liquid films and, therefore, to a smaller proportion of the fuel in the form of liquid droplets. Since the smaller droplets evaporated more rapidly, the Sauter Mean Diameters measured with closed-valve injection were larger than those in the model.

As a main result of the present study, it has been shown that the location of spray cone -higher data rate region- in the motored and firing engine is well approximated by the flow-rig experiment, as well as the temporal behaviour of droplets at their arrival into the cylinder. It can be argued that a motored camshaft is a fairly convenient tool allowing understanding of liquid film and direct spray mechanisms.

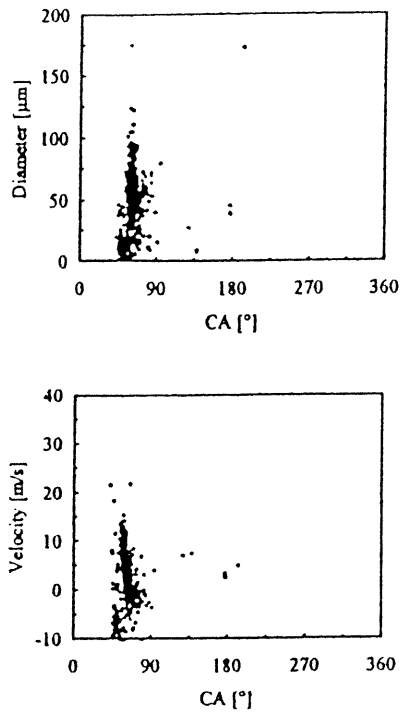


Fig.5.a) Injection against a closed valve

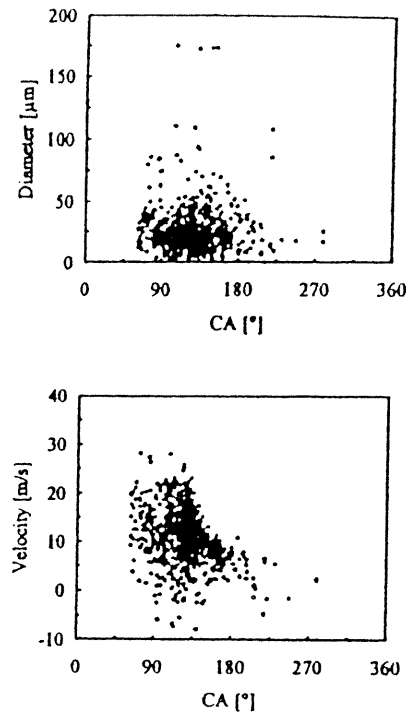


Fig.5.b) Injection against an open valve

Figure 5: Droplet velocity and diameter in the firing engine for injection against a closed and an open valve.

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