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Investigation of two-phase flows generated by cavitation inside high-pressure injection nozzles

Baz Ihab, Lance Michel, Champoussin Jean-Claude, Marié Jean-Louis

Lab. of Fluid Mechanics and Acoustics, UMR CNRS 5509, Ecole Centrale de Lyon,
Université Claude-Bernard de Lyon and INSA de Lyon , FRANCE
Michel.Lance@ec-lyon.fr

In this paper, we develop experimental techniques based on shadowgraphy and tomography techniques, associated with LIF, to visualize the two-phase flow structure into a typical nozzle geometry. The experiments were performed using a Common Rail system for generating periodic injection conditions. A transparent tip with sac and axial spray hole, drilled into quartz to allow optical access, is mounted over a standard type nozzle. The hole diameters of the nozzles vary in the range of 0.3 to 0.4 mm with a length/diameter ratio of 4. The experiments show that cavitation starts at the inlet of the orifice and develops to reach the exit. The local position and range of cavitation layers, lying between the flow and the nozzle wall and within the flow itself, are observed at different instants of the injection process. At high cavitation number ($K > 5$) and low Reynolds number ($Re < 12000$) the cavitation region spreads to the middle of the flow. However, when increasing the Reynolds number, the cavitation appears as a thin layer near the wall of the orifice. It is shown that small surface disturbances as well as the nozzle geometry have a strong influence on the flow inside the spray hole. Moreover, an hysteresis is observed when pressure is released.

1. Introduction

It is well known today that spray atomization in direct injection engines depends mainly on the cavitation of the flow within the nozzle. The challenge is to characterize high speed two-phase flows (> 200 m/s), at high pressure (> 70 Mpa), in very tiny channels (300-400 micrometers in diameter), in very unsteady conditions. In this paper, we develop experimental techniques based on shadowgraphy and tomography techniques, associated with LIF, to visualize the flow structure into a typical nozzle geometry. The first evidence of the role of cavitation in the atomization process stems from Bergwerk's paper (1959). Since this pioneering work, many experiments have been carried out to characterize the structure of the two-phase flow inside the injector channel, and its influence on the atomization of the liquid jet (Chaves et al., 1995, Arcoumanis et al. 2000, Baddock, 1999, Roosen et al. , 1997). As a matter of fact, the onset of the hydrodynamic instability of the liquid cylindrical jet, which is responsible for its break-up, is now recognized to originate from disturbances in the growing upstream in the injection channel. The latter may come from strong turbulence fluctuations and/or the presence of gas bubbles in the liquid associated with cavitation. In the range of very high pressure found in Diesel injectors, the occurrence of cavitation is unavoidable due to strong acceleration of the liquid at the inlet of the nozzle. The presence of sharp

edges in the injection device, which triggers detachment of the flow, still contributes to amplify this effect. Such a phenomenon is in principle well known at moderate pressures, and can be described with classical cavitation models. The situation is less clear for the present range of pressure and liquid velocity, for which non equilibrium effects may be expected. Moreover, the development of the flow inside the injection channel is conditioned by the existence of extremely strong shear (say 10^6 s^{-1}), which has no equivalent in usual situations. On the other end, the time scale of the flow is also very small, since the typical convection time in the nozzle is 10^{-5} s . These time scales have to be compared to the duration of the fuel injection, a few milliseconds. This suggests that a quasi-steady approximation could be adopted to describe the flow in the nozzle. This must be checked experimentally. As mentioned above, several studies have already been devoted to this problem. However, due to the experimental difficulties, the previous experiments were restricted to larger nozzle sizes and/or smaller pressures. The aim of the present study is to contribute to fill the gap between the experiments and the real flow conditions.

2. Experimental setup

Due the special pressure conditions encountered in the Diesel injection device, it proved necessary to use adapt a commercial injection device. Therefore, a standard type nozzle has been used. In order to perform optical measurements, the nozzle tip is replaced by an optically polished quartz, with the exact shape and dimensions of the sac and hole spray (fig. 1). The cylindrical orifice has a diameter of 0.4 mm and an aspect ratio of 4. The experiments were conducted using a Bosch Common-Rail injection system providing real unsteady Diesel injection conditions.

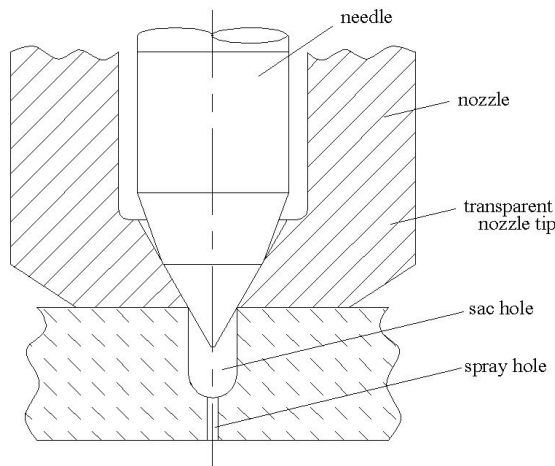


Fig. 1 Transparent Diesel nozzle

The main advantage of this system lies in the possibility to adjust the injection time and pressure, as well as the number of injection sequences. Since high rail pressures decrease the lifetime of the quartz nozzle tip, all our experiments are carried out at rail pressures smaller than 50 MPa and with energizing time of 2.5 ms. The fluid used is an oil with physical properties identical

to Diesel fuel. In particular, the values of density, viscosity and surface tension are respected. An advantage of this test oil for optical measurements is the good matching of the refractive index n to that of quartz ($n_{oil}=n_{quartz}=1.46$). Thus, reflection and refraction, when the light passes the internal surface of the quartz nozzle, is minimized. The oil is injected into a constant volume spray chamber capable of carrying high pressures (8 MPa). The optical system consists of a long-distance microscope and an intensified CCD camera (CCD-chip 1280x1024 pixels, exposure time down to 3ns, delay between two images down to 500 ns).

To reduce the blurring effects in the pictures caused by high flow velocities higher than 150 m/s, an exposure time of 20 ns must be used. As a light source, a xenon arc lamp is used (fig. 2) for shadowgraphy, and Argon-ion Laser is used for tomography with an optical setup to produce a light sheet thickness of less than 30 μm (fig. 3).

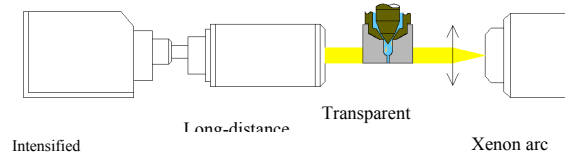


Fig. 2 Experimental setup for shadowgraphy

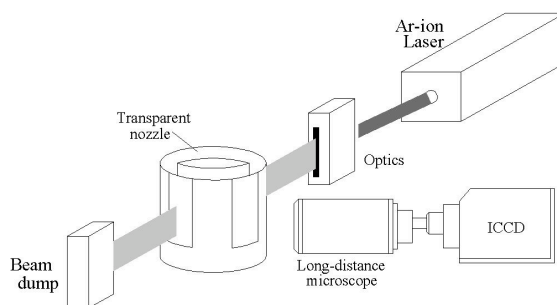


Fig. 3 Experimental setup for Laser tomography

In this work, a direct measurement of the sac pressure is made by using an AVL pressure transducer mounted on an injector tip drilled into steel and having the same dimensions as the transparent one.

3. Results and discussion

Due to the very small time scale of the flow, it proves impossible to resolve in time the whole sequence of the injection device. Therefore, phase synchronisation with periodic injection has been used. This supposes that the flow structure is also periodic and reproducible for each realization, which is obviously very unlikely. The visualizations presented here are only intended to shed a

qualitative view of the flow development. In order to bring more quantitative information it is necessary to account for some cyclic variations with phase averaging. So for each parameters setting, a sequence of about 50 pictures is recorded.

Figure 4 shows the time sequence of the injection, for a typical rail pressure of 250 bar. It is observed that this pressure decreases only very slightly with time, so that it can be assumed constant during the process. The flow rate is controlled by the lift of the needle, which can be adjusted to get different delays. The pressure in small volume before the injection channel (the sac) is an important parameter since it determines the actual liquid flow rate. It is worth noting the huge pressure drop associated with the path of the flow in the needle clearance.

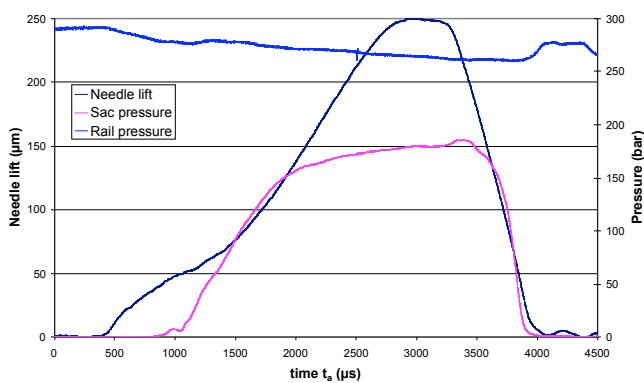


Fig.4 Needle lift, sac pressure and rail pressure during the injection cycle. $P_R = 30$ MPa, $t_e = 2.5$ ms

In figure 5 a reconstruction of the two-phase flow development is given. In the first image, the injector is filled up with liquid and a gas bubble is sucked from the chamber downstream when the needle lifts up. The next image shows clearly the onset of cavitation at the inlet of the injection channel. The development of a two-phase flow is observed in the next three pictures. The gas bubbles generated at the inlet are entrained by the high speed liquid flow and produce an annular-like structure, with a layer of gas close to the walls. At full needle lift the flow rate is maximum and the cavitation layer stretches till the end of the channel. Unfortunately, it was not possible with this device to observe the shape of the resulting spray. Other experiments however, in different conditions, have shown a reduced penetration length of the liquid jet in the chamber at this period of the injection cycle.

The mean velocity in the channel has been estimated from the displacement of gas bubbles measured between two images separated by 500 ns, assuming that the velocity slip is negligible. The resulting instantaneous Reynolds number is plotted in figure 6 for cycle duration.

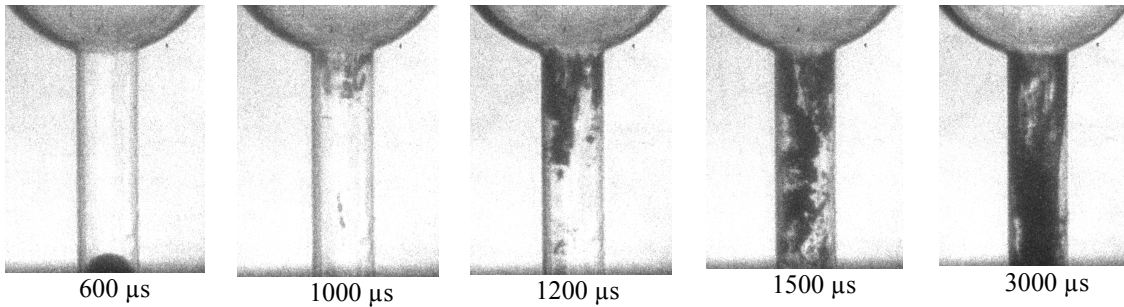


Fig. 5 Cavitation inside the spray hole : Rail pressure = 30 MPa, Back pressure = 0.1 MPa, Energizing time of the injector = 2.5 ms (Shadowgraphy images taken at different instants in the injection cycle)

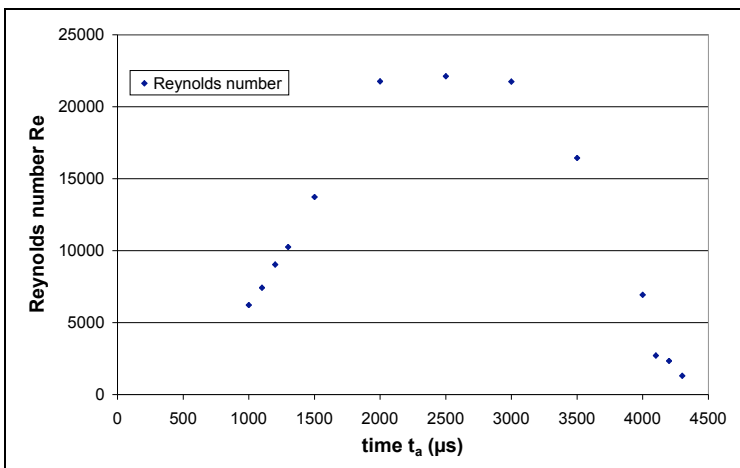


Fig. 6 Evolution of the instantaneous mean liquid Reynolds number. $P_R = 30$ MPa, $P_b = 0.1$ MPa, $t_e = 2.5$ ms

An important parameter for characterizing the cavitation process is the cavitation number, defined by :

$$K = \frac{P_s - P_b}{P_b - P_v}$$

where P_s is the nozzle sac pressure upstream to the flow orifice, P_v is the vapor pressure of the fuel and P_b is the downstream pressure. The evolution of this quantity, shown in figure 7, points out the high values reached by this parameter in this experiment. It is difficult to get quantitative data for the cavitation from the shadowgraphy pictures, since the light intensity is integrated along the chords of the cylindrical pipe. Laser tomography provides a better estimation of the sectional area occupied by the vapor phase. We define a cavitation rate as this area to the total area of the plane enlighten by the laser sheet. This quantity is shown in figure 8. The onset of cavitation is as expected advanced when pressure increases. Now, except for the beginning of the cycle, the influence of the pressure seems to be limited, and the cavitation rate reaches an asymptotic value of 20%. The accuracy of the measurements does not allow to discuss safely the apparent overshoot for

the lower pressure. Interestingly, cavitation re-increases when the needle is closing, despite of the decay of the cavitation number. It must be noticed that the high pressure drop for small needle lifts cause cavitation to occur near the needle passage, and therefore a higher void fraction may be observed in the injector. This effect is not very significant in practice for the corresponding flow rate is small.

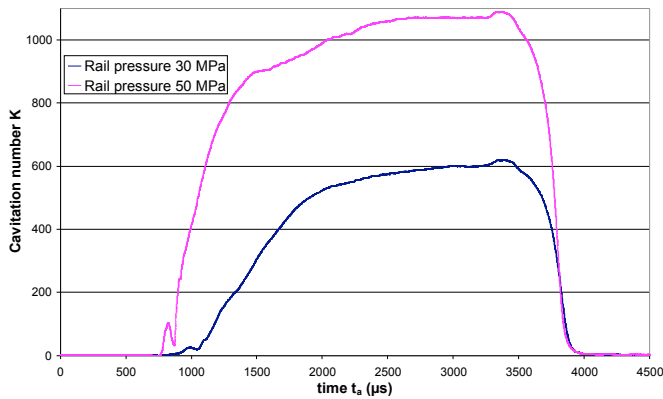


Fig.7 Evolution of the cavitation number during the injection cycle.

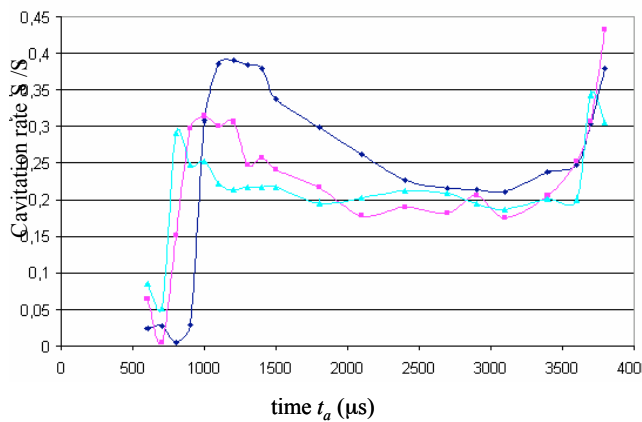


Fig. 8 Evolution of the cavitation rate during the injection cycle, for different rail pressure: blue 30MPa, pink 50 MPa, green 70 MPa. Pressure in the chamber 1MPa.

Figure 9 shows visualizations obtained with laser tomography coupled with PLIF. A fluorescent dye added to the test oil used for the experiments makes it possible to better distinguish between the liquid fluorescent phase and the vapor phase. It must be stressed out that the strong light absorption associated with the vapor layer and the dye permits to observe only one half of the flow (right side in the figures). The vapor layer is well delimited, the resolution however does not show its fine

structure, likely a layer of small bubbles. An interesting effect is the hysteresis observed when the needle is closing. As a matter of fact, under quasi-steady conditions, it should be expected that the flow structure would be the same for identical cavitation numbers, or in other words, that the opening and closing phase would be similar (except for the very beginning and the very end, as discussed above). This is clearly not the case here, which perhaps indicates that the role of activated cavitation sites on the wall could be significant.

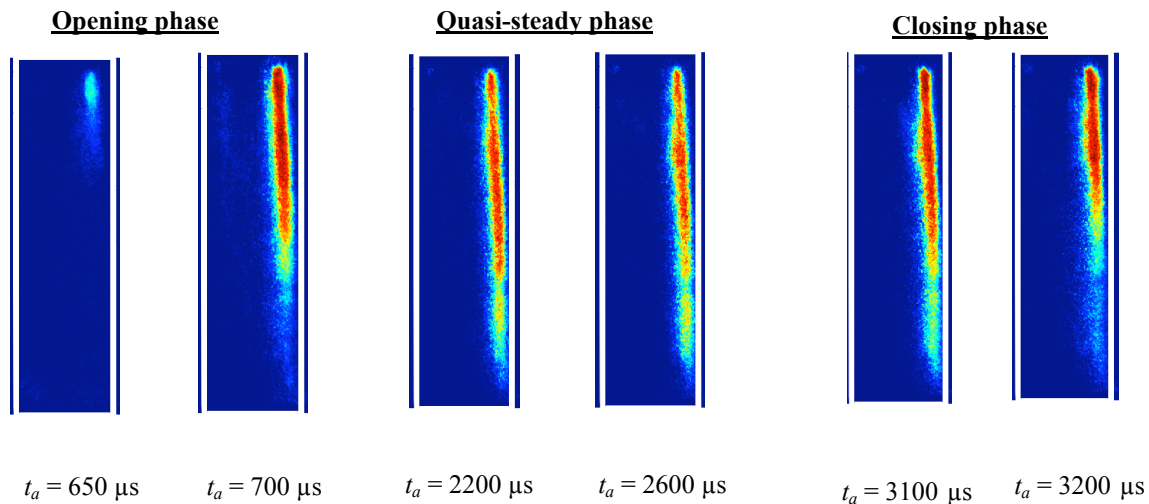


Fig.9 Visualization of the flow in the injector during the injection cycle using PLIF

4. Conclusion

It has been possible in this work to visualize the two-phase flow developing in a small fuel injection channel, for very severe flow conditions. The onset and the development of cavitation have been characterized. Further efforts are needed to still improve the accuracy of the data, and to couple the structure of the flow and that of the atomizing jet in the chamber, as well as the size distribution of droplets in the spray.

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