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Visualisation of cavitation in diesel engine injectors

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Abstract — The phenomenon of cavitation and its occurrence in diesel engine injector nozzles is discussed and examples are given of cavitation patterns formed in the sac volume and holes of multi-hole nozzles under realistic operating conditions. Experiments performed in real-size production nozzles incorporating glass windows have revealed the existence of string cavitation initiated within the sac volume and film cavitation formed at the inlet to the holes which interact along the hole length creating a highly turbulent two-phase flow at its exit. Although there is a consensus that the two-phase hole flow structure, which varies with cavitation and Reynolds number as well as the needle lift, has a noticeable effect on the subsequent global spray characteristics, details of the link between hole cavitation and fuel atomisation remain largely unclear. © 2001 Éditions scientifiques et médicales Elsevier SAS

cavitation / holes / diesel injectors

Résumé — **Visualisation de la cavitation dans les injecteurs de moteurs Diesel.** Le phénomène de cavitation et son apparition dans les injecteurs des moteurs Diesel est discuté et des exemples de cavitation dans les « sac » et les orifices pour des conditions d'opération réalistes sont donnés. Les expériences réalisées avec des injecteurs industriels pourvus de fenêtres d'observation en verre ont montré l'existence de lanières de cavitation dans le volume du « sac » et des films de cavitation à l'entrée des orifices. Ces deux types de cavitation interagissent et long des orifices et produisent en sortie un écoulement diphasique fortement turbulent. Il y a un consensus pour reconnaître que l'écoulement diphasique dans les injecteurs, qui varie avec le nombre de cavitation, le nombre de Reynolds et la levée de l'aiguille, a une importance notable sur les caractéristiques globales de l'atomisation du jet. Cependant, la liaison entre celle-ci et la cavitation dans les orifices reste encore obscure. © 2001 Éditions scientifiques et médicales Elsevier SAS

cavitation / orifices / injecteurs Diesel

1. INTRODUCTION AND BACKGROUND

In many engineering applications where cavitation takes place, such as in ship impellers and pumps, the collapse of cavitation bubbles is considered to have undesirable effects on the mechanical integrity of the relevant components, through surface erosion, and their mechanical efficiency due to reduction of the overall density of the two-phase mixture. The mechanical efficiency is also decreased because the pressure distribution is altered and, in particular, the lowest possible pressure is limited to the vapour pressure of the working liquid. Moreover, the drag is increased because of the thickening of the wake as a result of the formation of a cavity. However, in engine fuel injection systems such as diesel multi-hole injectors, collapse of the cavitation bubbles in the nozzle holes is expected to enhance fuel atomisation [1], through generation of smaller droplets which vapourise faster enhancing fuel/air mixing and reducing ignition delay. It is, thus, becoming clear that for development of more efficient high pressure fuel injection systems, control of cavitation may become a prerequisite. In this context, cavitation can be defined as the low temperature vapourisation of the more volatile components of the multi-component diesel fuel in regions of the flow where the static pressure drops below the vapour pressure of the fuel. The onset of cavitation is associated with the process of nucleation which represents the bubble precursor stage and can be of the homogenous or heterogeneous type; a summary review of the physics of cavitation is provided in [2] together with an extended reference list. In the case of homogenous nucleation, nuclei are created due to the thermal motion of the bulk fluid while in the heterogeneous case the nuclei can be impurities or dissolved gas in the liquid fuel and are more associated with solid boundaries where, depending on the wall surface roughness and temperature, can be concentrated in microcavities, initiating cavitation near the wall. The degree of the dissolved gas is another important factor affecting nuclei size distribution since a higher concentration of gas gives rise to increase in the nuclei population number and size. Finally, the wall surface roughness and instantaneous temperature have a controlling effect on the active nuclei sites near the walls by determining the initial bubble size distribution in association with the homogeneous nucleation sites.

Although a number of studies have provided evidence of the existence of cavitation and its dependence on injection pressure, the detailed structure and cavitation regimes remained until recently unknown. Most of these studies have been performed on large scale transparent models since real-size production nozzles have very small dimensions (hole diameters of 0.15–0.18 mm), while operating under very high injection pressure ($\geq$1 300 bar) over very short times. In most cases the Reynolds number was kept similar to that in real-size nozzles, with a few limited efforts [10, 11] to simulate at the same time the cavitation number as well as to match the refractive index of the liquid to that of the acrylic wall [3, 4, 11], thus allowing laser Doppler velocimetry (LDV) to be applied for measuring the liquid velocity and turbulence. In recently reported work [13–15] in multi-hole large-scale transparent nozzles has revealed quite clearly the co-existence of two forms of cavitation initiated in the sac volume and nozzle hole, respectively, independent of nozzle geometry; more details of the flow patterns will be given in the next section. Parallel to these studies in multi-hole nozzles, experiments were reported in [16–18] in real-size single-hole axisymmetric nozzles operating with injection pressures up to 600 bar. In [18] the influence of hole inlet geometry on cavitation was examined in detail using differently ground inlet edges under constant volumetric flowrate. Surprisingly, the images of the exiting spray revealed very small differences between the three nozzles despite the significant variations in the hole cavitation structure. The authors have thus concluded that, irrespective of the formation of cavitation films, an intact liquid core is present in the spray leaving the nozzle even at high injection pressures [17]. Contrary to these observations, in a similar real-size single-hole configuration [19] has revealed that collapse of the cavitation bubbles, which starts at the nozzle exit, disrupts the liquid column enhancing fuel atomisation. In addition, velocity measurements using cavitation bubbles as traces have confirmed that the liquid jet velocities at the nozzle exit are higher than those deduced from volumetric discharge measurements, which implies that the effective hole exit area is smaller than the geometric area due to the presence of cavitation bubbles and structures [20].

The uncertainty about the relevance of the flow patterns formed in large-scale multi-hole nozzles [14, 15] and those in real-size single-hole nozzles [16–20] has prompted an investigation into a real-size multi-hole nozzle [21] where visualisation into one of the six holes was achieved by incorporating a quartz window into the hole wall and using a fast, high resolution CCD camera equipped with high magnification lenses to visualise the flow. The incentive for this investigation has been the expectation that the flow in the sac volume of multi-hole nozzles is different than that in single-hole ones due to the interaction between the flow entering adjacent holes which can affect cavitation through formation of additional cavitation structures. More details about the flow regimes are given in the next section where comparisons are made between the cavitation patterns in identical large-scale and real-size nozzles under similar flow and cavitation conditions.

2. RESULTS AND DISCUSSION

In what follows, the main conclusions from recent studies [13–15, 21] performed in enlarged and real-size six-hole vertical nozzles of the sac-type are summarised and discussed. Simultaneous matching of the Reynolds and cavitation numbers in the range $Re = 15\,000-44\,000$ and $CN = 0.6-18$ has allowed direct comparison between the cavitation regimes present in real-size and large-scale nozzles. The Reynolds number, *Re*, is defined as $Re = U_{\mathrm{inj}} D/\nu$, where U_{inj} is the liquid bulk velocity in the injection hole, D is the injection hole diameter and ν is the liquid kinematic viscosity. The cavitation number, *CN*, is defined as $CN = (P_{\mathrm{inj}} - P_{\mathrm{back}})/(P_{\mathrm{back}} - P_{\mathrm{vapour}})$, where P_{inj} is the injection pressure, P_{back} is the back pressure acting at the hole exit and P_{vapour} is the liquid vapour pressure.

2.1. Large-scale nozzle

The investigation was performed in the case of the large-scale transparent nozzles in a purpose-built steady-flow refractive index rig where the working fluid (mixture of two hydrocarbon fluids) exhibited at 25 °C identical refractive index to that of cast acrylic, permitting uninterrupted optical access into the nozzle sac volume and hole irrespective of geometrical complexities. This has allowed very clear images to be obtained of the cavitation structures formed at various Reynolds and cavitation numbers thus providing identification of a wide range of cavitation regimes that may be present in real-size nozzles, where there can be blurring of the images of cavitation due to the much higher flow velocities. The results in the large scale sac-type nozzle [14] revealed that increasing the cavitation number resulted in formation of different cavitation hole flow regimes. Initially a bubbly flow structure was identified (incipient cavita-

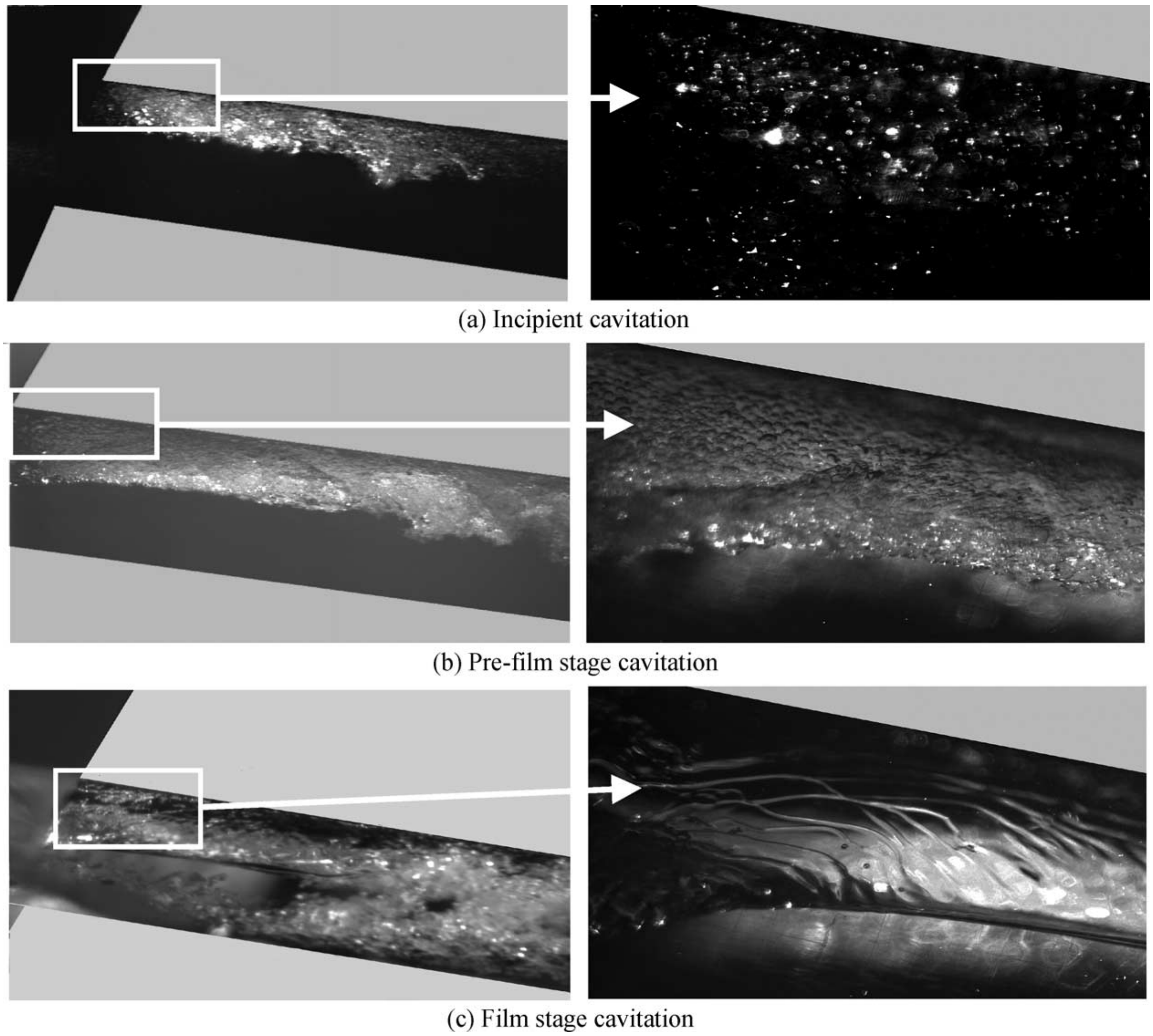

Figure 1. Cavitation regimes identified in large-scale sac-type hole nozzle.

tion) followed by pre-film stage cavitation consisting of a dense bubble cloud and film type cavitation (vapour film) at which complete flow separation takes place at the nozzle hole inlet. Although these geometrically-induced cavitation patterns were found not to depend on Reynolds number, the development of the cavitation structures was strongly affected by both needle lift and needle eccentricity. Examples of these cavitation regimes are given in *figure 1*. Surprisingly, in addition to hole cavitation, cavitation strings were observed to form inside the sac volume which seemed to develop transiently and periodically between adjacent holes (*figure 2*). What may prove to have major practical importance is the interaction of these cavitation strings inside the hole with the cavitation films already formed on the upper part of the hole surface, giving rise to turbulence enhancement and hole-to-hole variations in the two-phase mixture exiting the hole. Thus, despite the axisymmetric geometry of the vertical multi-hole nozzle, variations in the flow pattern between holes are likely to happen due not only to geometric effects such as transient needle eccentricity but also due to the complex two–phase flow present in the sac volume and holes after the onset of cavitation.

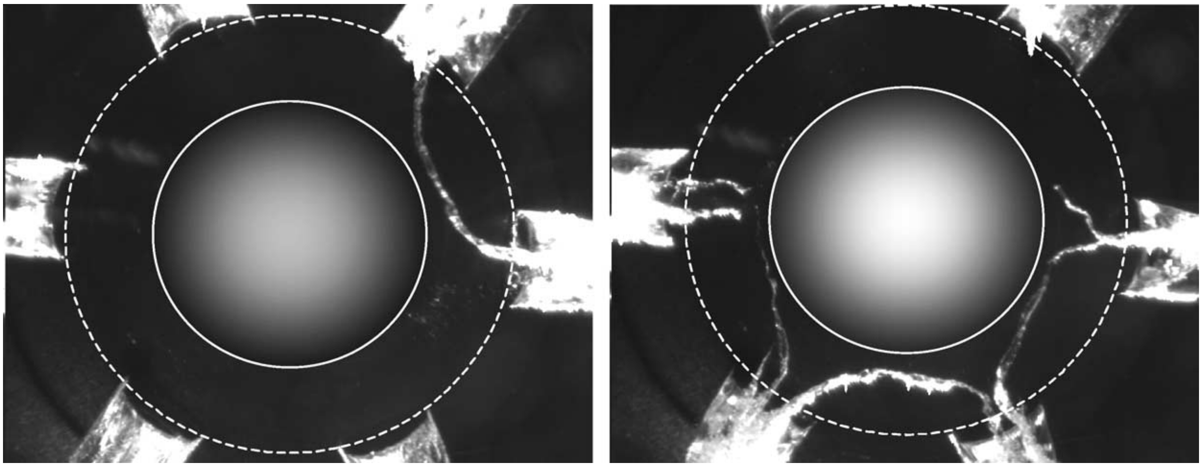

Figure 2. String-type cavitation in the sac volume of the sac-type nozzle.

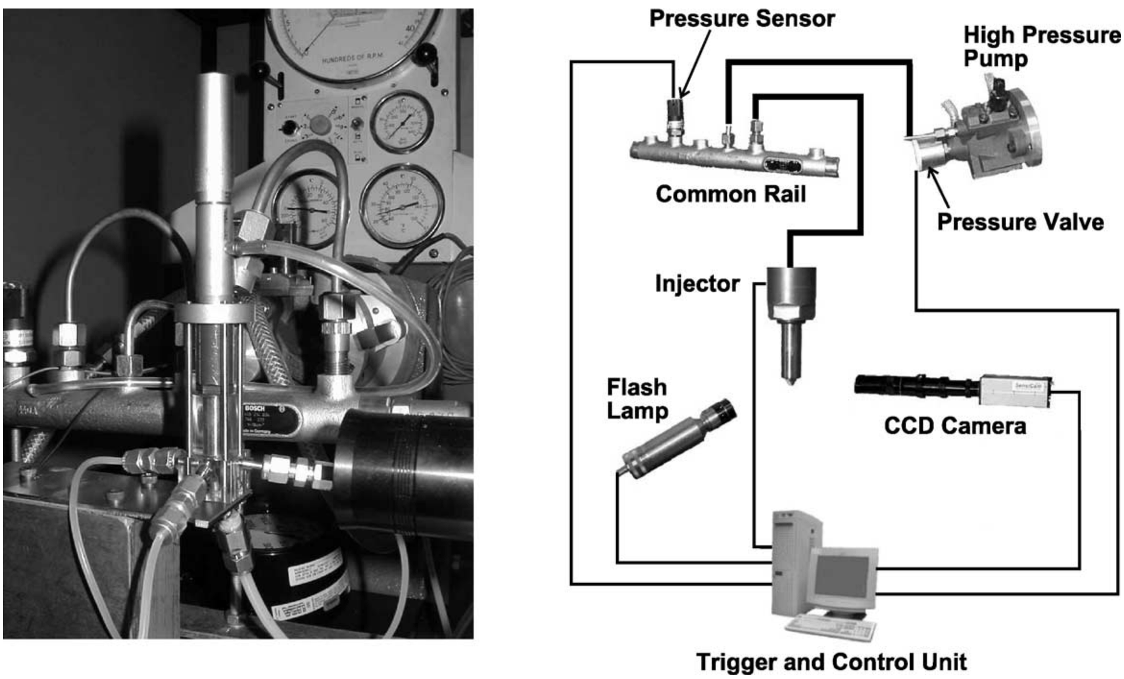

Figure 3. Photograph and schematic of multi-hole real-size nozzle visualisation system.

2.2. Real size sac-type nozzle

Following the investigation of cavitation in transparent large-scale nozzles, a production six-hole nozzle was modified to allow observation of the flow in one of the holes under similar Reynolds and cavitation numbers [21]. To allow direct comparison of the cavitation patterns, the needle lift of the production injector was fixed at two levels corresponding to the first and second injection stage, similarly to the large-scale nozzle; thus the real-size nozzle was also operated under steady-state conditions. A schematic of the experimental rig is shown in *figure 3*.

The images of the flow obtained in the real-size nozzle revealed that, relative to the large-size model, a higher cavitation number is required to initiate hole cavitation.

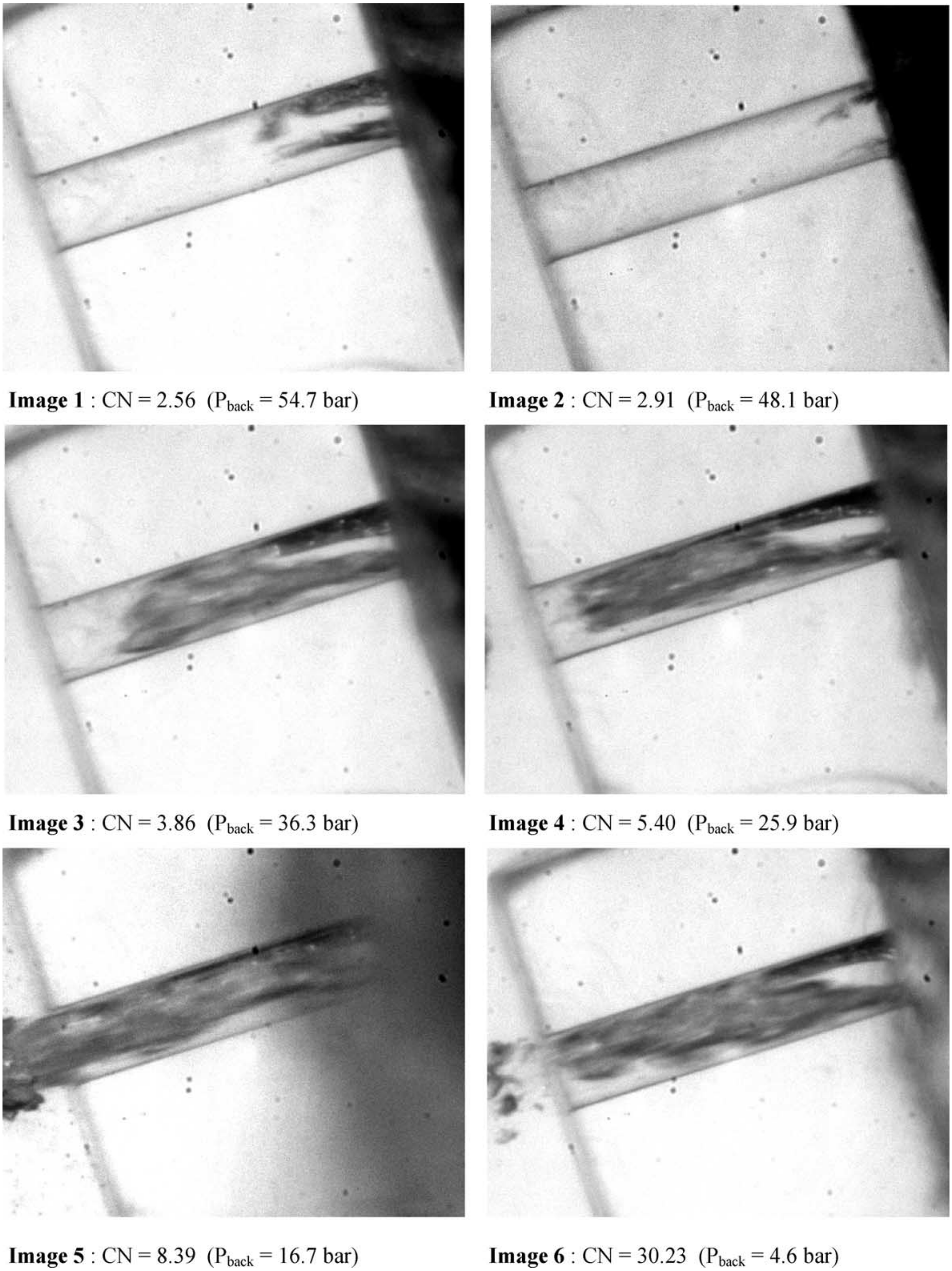

Figure 4. Effect of cavitation number through back pressure variation on hole cavitation (needle lift = 0.30 mm, $Re = 12\,621$, $P_{inj} = 140$ bar).

However, once cavitation starts, the sequence of the cavitation regimes resembles closely those formed in the large-scale nozzle and especially the third stage of film cavitation where the dense bubble cloud coalesces to form an extensive vapour film attached to the upper wall of the nozzle hole (*figure 4*). Since the thickness of the cavitation film does not seem to scale with hole size, a relatively larger vapour volume fraction was identified to be present in the real-size nozzle. The main difference identified in the two flow patterns is related to the residence time and collapse time of the formed bubbles inside the injection hole. In contrast to the large-scale models, the cavitation bubbles in the real-size nozzle were found to collapse before reaching the hole exit especially at low Reynolds and cavitation numbers when the collapse time decreases and the residence time of the bubbles increases. At sufficiently high cavitation and Reynolds numbers, when some cavitation structures were found to extend up to the hole exit, the images revealed that the film formed at the hole entrance breaks down into a large number of bubbles and vapour voids at approximately the re-attachment point of the recirculation zone. The end result is a two-phase flow extended over the whole cross-sectional exit area, which is expected to enhance fuel atomisation in the emerging fuel spray.

Similarly to large-scale nozzles, a dynamically-induced form of cavitation was identified to occur inside the sac volume in the form of strings or vortices. This additional type of cavitation was evident in the real-size nozzle only at high needle lifts, contrary to the large-scale model where strings were present even at low lifts, albeit at a reduced frequency of occurrence. Shortly after the cavitation strings entered the holes from their bottom corner, they interacted with the pre-existing vapour film creating a foam-like cloud of cavitation bubbles that extended up to the hole exit.

3. CONCLUDING REMARKS

The identification of the formation of both geometrically-induced hole cavitation, initiated at the hole entrance and persisting in the form of vapour films, and dynamically-induced cavitation strings or vortices formed in the sac volume which enter the holes interacting with the films, represents a significant breakthrough in the understanding of cavitation in diesel engine injector nozzles. Furthermore, the observed similarity in the cavitation structures of large-scale and real-size multi-hole nozzles implies that large-scale transparent injectors, which offer better resolution and more easily quantifiable flow conditions, can be used in further studies provided the cavitation and, to a lesser degree, the Reynolds number of the flow are matched to those of the production nozzle.

With this improved understanding of the cavitation patterns present in production injectors as background, it becomes a matter of time before the link between cavitation-induced atomisation and spray characteristics is identified and physically described. It is expected that in the not too distant future two-phase CFD models will become available which will incorporate sub-models for homogeneous and heterogeneous nucleation as well as for bubble dynamics, thus allowing the calculation of the two-phase flow at the nozzle exit and the subsequent spray development in diesel engine cylinders under the whole range of engine operating conditions. Validation of these two-phase CFD models with experiments, such as those described in this paper and others focussing on the temporally and spatially-resolved droplet characteristics near the nozzle exit, may allow their use as design tools by fuel injection equipment manufacturers in their effort to assist in the reduction of NOx and particulate emissions to levels below those dictated by the Euro4 emission regulations.

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