

FLOW AND CAVITATION STRUCTURE IN A SCALED-UP MULTI HOLE OPTICAL DIESEL NOZZLE

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ABSTRACT

An attempt has been made to study and understand the internal nozzle flow and cavitation structures in a two-hole scaled up optical diesel nozzle. The study shows that cavitation is very sensitive to small perturbations caused by the flow as well as the eccentricity of the needle. Two types of cavitation structures were observed under steady state flow condition, when the needle was lifting (intermittent cavitation structure was observed) and when the needle was held at fixed lift positions (intermittent and continuous cavitation were observed). The global profiles of the intermittent cavitations were similar to that of continuous cavitation. But under transient operation of needle motion, intermittent cavitation was observed always during the needle lifting process and the cavitation disappeared before the needle reached the maximum lift position. The flow and cavitation structures prevailing in the nozzle sac and the nozzle holes under needle motions are very different compared to the case of fixed needle lift positions.

INTRODUCTION

Liquid jet break-up has a significant influence on the spray evaporation, mixing and combustion process in diesel engines. The exact mechanism leading to the break-up of the liquid jet has not been completely understood due to the dense nature of the spray near the nozzle. It has been proposed by [1] that amongst others such as turbulence, aerodynamic and surface instabilities, the nozzle geometry, nozzle internal flow and cavitation have a significant influence on the near nozzle spray break-up. It had been identified by [2] that the generation of cavitation bubbles in the nozzle was a possible contributor to the break-up and dispersion of the liquid jet near the nozzle exit. The cavitation bubbles generated in the nozzle hole increased the ruffles in the spray and eventually at higher flow rates the jet was glass-like and non-atomising jet. Similar effects of geometry induced cavitation in nozzles were observed in the work of [3 and 4] and the non atomising jet was referred as hydraulic flip.

The flow pattern in the sac of a single hole planar nozzle was studied by [5]. It was observed that when the needle was offset to the hole axis the flow within the sac volume was asymmetric, which subsequently resulted in a large recirculating vortex flow in the sac volume. In a similar investigation, Dan [6], observed two counter rotating vortices on either side of the needle in the sac volume of a single hole axis symmetric optical nozzle. The intensity of the vortices varied with different needle lifts.

A detailed study on the flow in a six hole optical nozzle was carried out using a scaled-up optically accessible nozzle by [7]. The flow in the scaled-up optical nozzle flow was scaled according to the cavitation and Reynolds number of the real-size nozzle. In their work the cavitation structures originated from the hole entrance and the cavitation structures were liked from hole to hole in a random manner. It was also

shown that the needle eccentricity had a strong influence on the cavitation structure. In order to enhance the understanding of the cavitation phenomena in diesel nozzles, we carried out a fundamental study in a two hole optical nozzle with a needle. The influence of needle positions and the needle motion on the flow and cavitation structures are presented in this work.

EXPERIMENTAL SYSTEM

The schematic of the experimental test setup is shown in Figure 1. In order to visualize the internal flow within the nozzle holes and in the sac, a scaled-up two hole nozzle was constructed using a Plexiglas and the diameter of the nozzle hole is 4.80 mm diameter. The optical nozzle was scaled up 20 times and was built together with a needle to study the various internal nozzle flow phenomena occurring within the holes and in the sac due to different needle lifts, different flows rates and due to the continuous motion of the needle. Throughout this investigation water was used as a working fluid and the water flow rate was measured using a flow meter located just before the inlet to the optical nozzle. As shown in the schematic the inlet flow was split in two and fed into the optical nozzle, the supply of water through two opposite inlet ports of the injector enabled to have a symmetrical inflow to the nozzle. The needle could be lifted and fixed at a particular position through a nut and a thread arrangement which was fabricated on the top of the needle.

The optical nozzle was illuminated using a copper vapour laser, which was operated at 10 kHz, and the flow and cavitation structures prevailing within the optical nozzle were visualized using a high speed camera at a frame rate of 10,000 frames per second. The experiments were carried out at different flow rates, under different needle lift positions and by continuously moving the needle. For each operating conditions, care was taken to remove all the air bubbles.

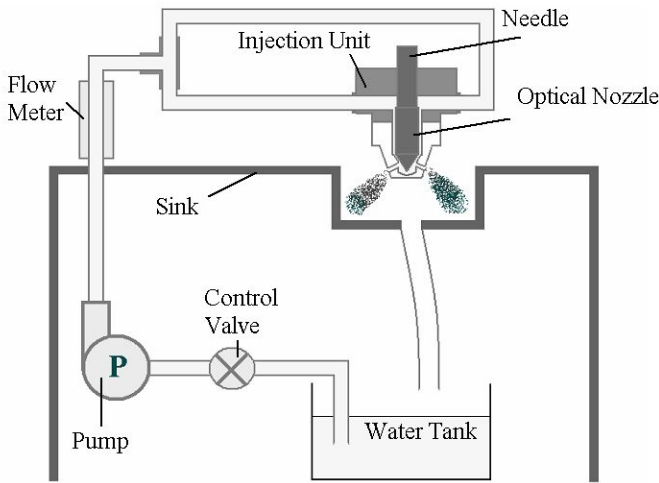


Figure 1. Schematic representation of the experimental set-up

RESULTS

Regimes of cavitation

In this investigation, cavitation structures were observed to occur under specific conditions of flow rate and needle lift positions. As the flow and the needle lift positions were varied, three distinct flow regimes were observed in the optical nozzle.

The first type of flow corresponds to non-cavitating regime, which was observed at lower flow rates and at all needle lifts. the second type of the flow corresponds to continuous cavitation regime, during this flow regime the cavitation structures were connected from hole to hole and the cavitation structures were running through the sac volume and it was observed all the time.

While the third type of flow corresponds to discontinuous cavitation regime, basically the cavitation was observed almost in the same geometrical locations. For a given flow and needle lift condition the cavitation was discontinuous and intermittent. These structures were not observed all the time as continuous cavitation. Intermittent cavitations appeared and disappeared within a short period of time.

Based on these observations, the occurrence and non-occurrence of cavitation under different nozzle flows and different needle lift positions are mapped in Fig. 2. In this figure, a thin line was used to differentiate the boundary limit, but in reality, boundaries are overlapping across the thin line due to the unsteady nature of flow and cavitation within the nozzle. Experiments were carried out under five operating points as shown in Figure 2.

Point 1 corresponds to a needle lift of 2 mm and a flow rate of $70.8 \times 10^{-6} \text{ m}^3/\text{s}$, ($Re=9\ 370$).

Point 2: corresponds to a needle lift of 2.5 mm and a flow rate of $108 \times 10^{-6} \text{ m}^3/\text{s}$, ($Re=14\ 300$).

Point 3 corresponds to a needle lift of 1.8 mm and a flow rate of $83.3 \times 10^{-6} \text{ m}^3/\text{s}$ ($Re=11\ 000$).

Point 4 corresponds to a needle lift on 2 mm and a flow rate of $117 \times 10^{-6} \text{ m}^3/\text{s}$ ($Re=15\ 400$).

Point 5 corresponds to a needle lift of 1.3 mm and a flow rate of $91.7 \times 10^{-6} \text{ m}^3/\text{s}$ ($Re=12\ 100$).

Where the Reynolds number (Re) was calculated using the following relations:

$$Re = \frac{V d \rho}{\mu}$$

Where V is calculated thanks to:

$$V = \frac{Q}{A} = \frac{Q}{2 \pi (d^2/4)}$$

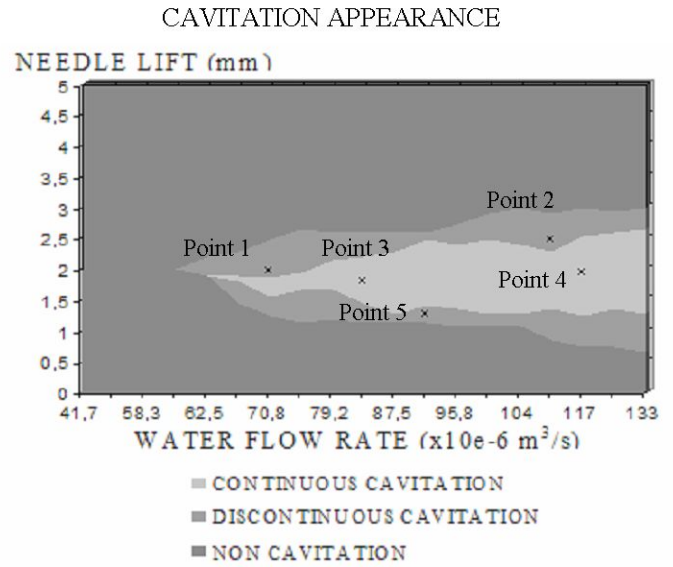


Figure 2 - Map of nozzle operation and different cavitation regimes together with selected operating points.

Intermittent cavitation (Appearance)

Operating point 1 corresponds to a lower flow rate compared to the operating point 2. These two operating points are chosen in such a way that they are located in the intermittent cavitation zone. The structure of cavitation prevailing within the nozzle under operating points 1 and 2 are very similar. Thus in this section only the cavitation structures pertaining to operating point 2 are discussed and the selected frames of the high speed images are shown in Figure 3, which can be seen on the next page.

As described the optical nozzle was uniformly illuminated using a Cu vapour laser (green light) from the bottom of the nozzle. Due to round surfaces of the sac as well as the nozzle hole there were reflections; the angle of illuminations were adjusted to minimize these reflections. However these reflections could still be seen in all the images and these reflections should not be mistaken for cavitation structures; they are labelled in the first frame of each figure.

No cavitation was observed in Fig. 3(a) and it could be seen that the cavitation was first observed towards the exit of the right hole, Fig. 3(b). These cavitation structures appeared to be in the form of bubbles, which were traveling towards the inlet of the hole from the hole exit, in the direction against the fluid flow as observed in Figure 3(c) – 3(e).

These travelling cavitation bubbles appeared to be in the form of a string of bubbles, which travelled from the hole exit to the bottom part of the right hole inlet entrance and into the sac. From the sac these string like cavitation bubbles headed towards the opposite hole entrance and through the hole to its exit as seen in Fig. 3 (h) – 3 (l).

The presence of the needle in the sac causes a strong recirculation zone in the region downstream of the needle in the sac volume, which subsequently leads to the formation of a vortex. As a result of which the pressure in the sac volume is lower in the region below the needle. When the string of cavitation bubbles reaches the sac hole, these bubbles can

grow in its size and at the same time there could also be inception of new cavitation bubbles in the sac.

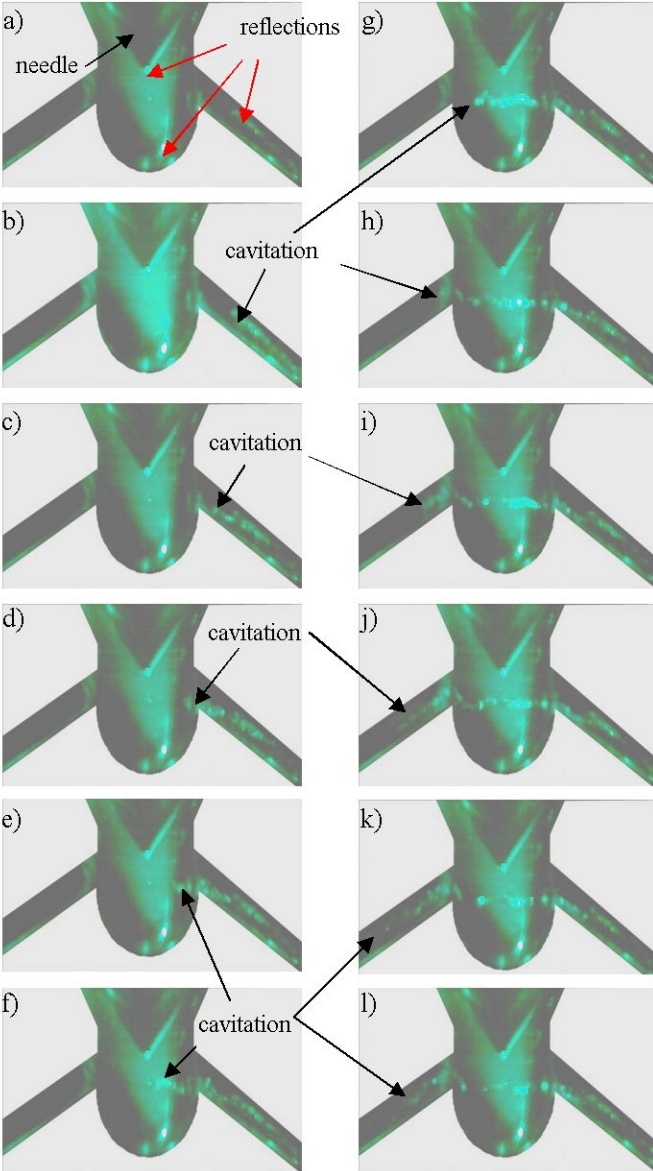


Figure 3 – Beginning of cavitation for Point 2

Furthermore the profile of cavitation structure within the nozzle sac appears to be bent due to the unsteady and oscillating nature of the flow, as observed in the high speed images, Fig. 3(g) - 3(l). The unsteady and oscillating characteristics of the string in the sac could be associated with the presence of vortex in the sac volume. As the string enters the opposite (left) hole and continues its way along the axis of the left hole the cavitation appears bubbly more at the hole entrance. Moreover these cavitation structures broke-off at the boundaries between the sac and the hole, Fig. 3(h) - 3(i).

In order to acquire details about the cavitation under intermittent cavitation condition, high speed images were acquired under a higher magnification condition covering only the nozzle hole and a part of the nozzle sac volume as shown in Figure 4. The cavitation bubbles traveling from the right hole through the sac to the left hole entrance could be seen in Fig. 4(a). Due to the unsteady nature of the recirculating/vortex flow in the sac, the cavitation bubbles in the sac are oscillating about its position. As a result of which it can be seen in subsequent frames, Fig. 4(b) – 4(d), the cavitation bubbles in the sac hole tends to move up to get into

the inlet of the left hole entrance and along its axis. After entering in the hole, it could be seen that the vortex flow present within the nozzle hole entrance disrupts the cavitation bubbles and it breaks off further into more number of bubbles just after its entrance into the hole, as shown in Fig. 4(e) and 4(f).

In addition to this, more cavitation bubbles were also produced within the hole entrance as shown in Fig. 4 (g) and (h). In general, these cavitation bubbles were attached more towards the lower surface of the nozzle hole. From the high speed images it was also observed that there was shedding of cavitation bubbles from the cavitation cloud as observed in Fig. 4(j) and 4(k).

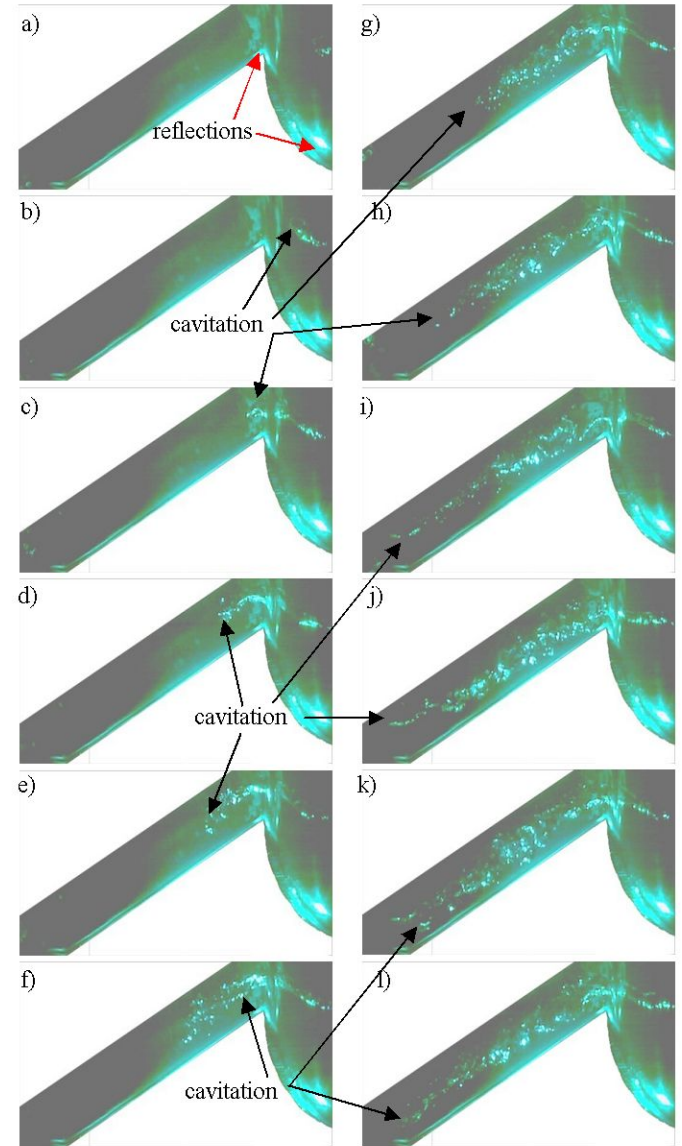


Figure 4 – Beginning of cavitation for Point 2

Under this operating condition (of intermittent cavitation), the cavitation always originated from the right hole exit. The reason for initiation of cavitation at the right hole was not clear, but this may be linked to a slight eccentricity of the needle in the sac or may be it could be a geometry induced effect. It is also speculated that under certain needle lifts and flow conditions the presence of strong vortex in the nozzle sac can extend into the hole, which may also cause the cavitation/air bubbles to be sucked into the hole against the flow direction.

Intermittent cavitation (Disappearance)

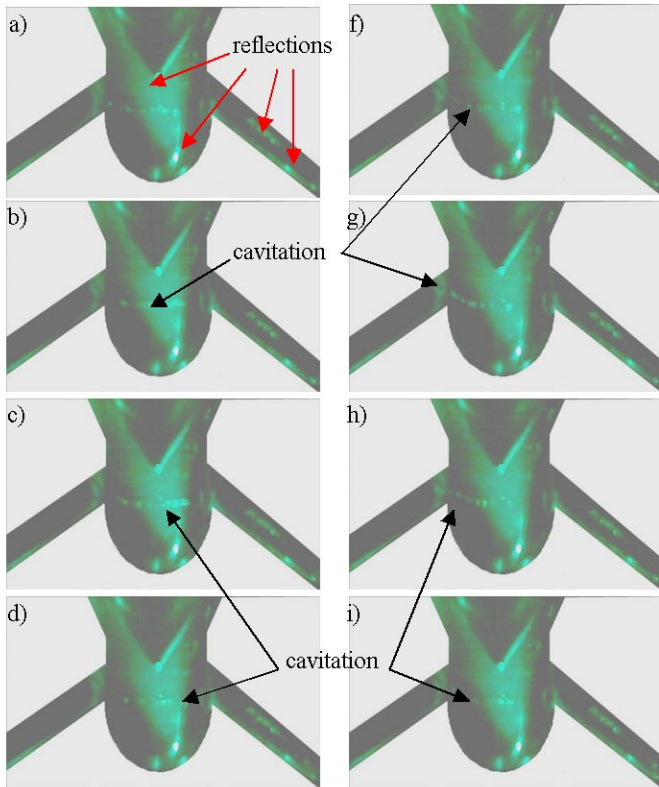


Figure 5 – End of cavitation, corresponding to point 2

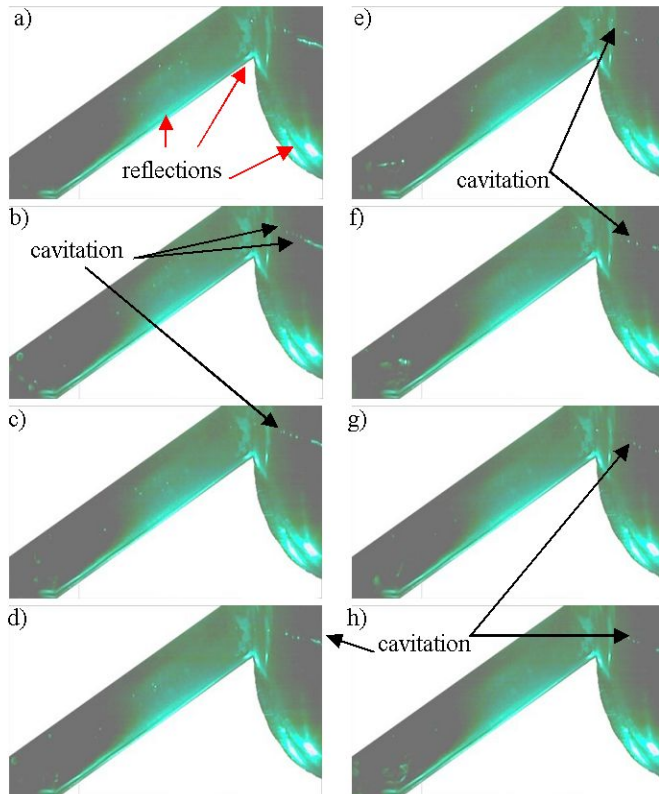


Figure 6 – End of cavitation

The disappearance of intermittent cavitation was more slow and gradual. High speed images corresponding to the operating point 2, which are presented in Fig. 5 shows that the cavitation string became thinner all along its profile (from the right hole to the left hole). As shown in Figure 5(a) & 5(b), the moving strings became weaker and were in contact with

the lower inlet corners of both the holes, the cavitation string was less oscillating. During this stage, the cavitation bubbles within holes became very scanty. Gradually some bubbles followed the flow, while some of the bubbles disappeared within the holes. Eventually the vortex string like cavitation in the sac volume became weaker and pinched off the string, which eventually led to the disruption of the string. Finally, few bubbles survived in the low pressures regions of the sac volume for a relatively longer time period before it was completely disappeared from the nozzle sac as shown in Fig. 5(c) – 5(i).

Similar observations were made under higher magnification, of the flow corresponding to operating point 5, as shown in Figure 6.

Continuous cavitation

Continuous cavitation was observed under the operating point 3. Under these two operating conditions the cavitation appearance and their structures are very similar. Thus only the results of the operating point 3 are presented in this paper, as shown in Fig. 7.

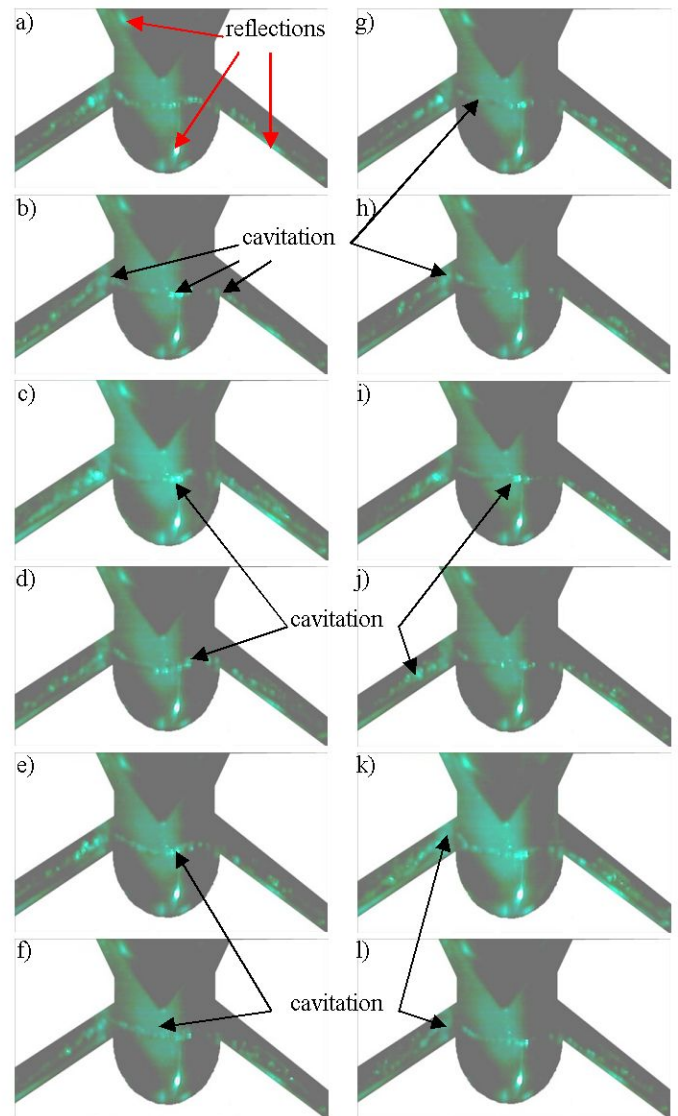


Figure 7 – Continuous Cavitation

In this regime, the cavitation bubbles came from the right hole exit. These bubbles were continuously connected to the right and left holes. These oscillating cavitation structures in

the sac volume were prominent under all flows conditions in the continuous cavitation regime. The string structure broke-off into a cloud of bubbles at the right inlet corner.

On the global level the structure and the profile of continuous and intermittent cavitation occurring in this nozzle were very similar.

Cavitation appearance and disappearance under needle motion

The influence of needle motion on the flow and the cavitation structures prevailing within the nozzle was studied by simultaneously imaging the nozzle flow using the high speed camera and by lifting the needle rapidly to its maximum lift position and by lowering the needle to the close position. Even though the time scales of the real size nozzle are different from that of the scaled-up nozzle, these observations have provided an insight on the formation, transport and disappearance of cavitation occurring within the nozzle during these transients.

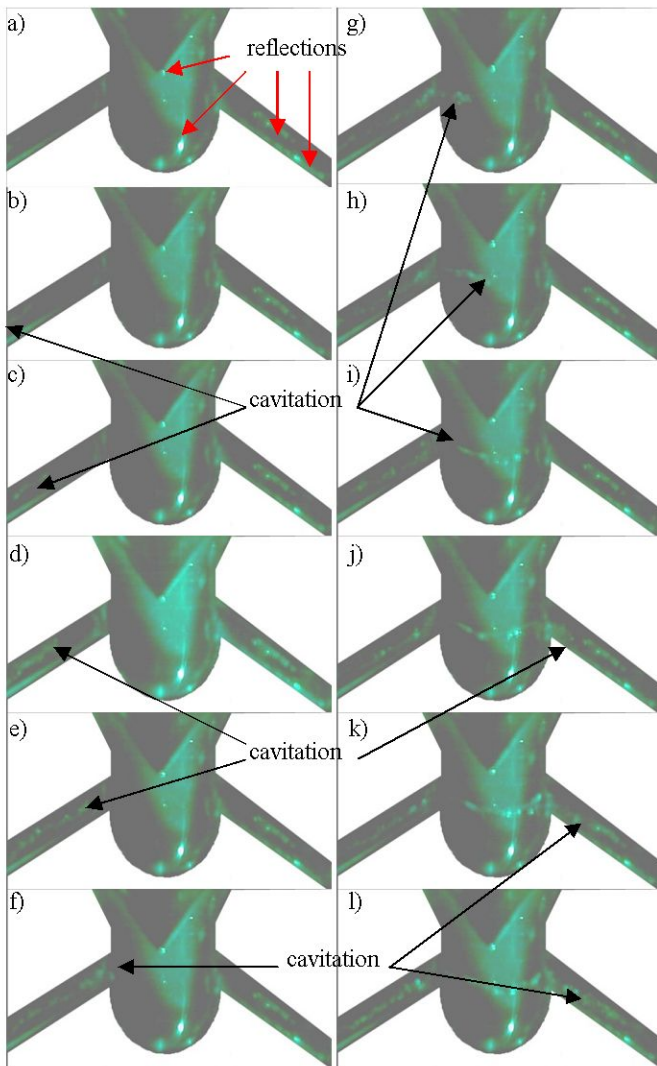


Figure 8 - Appearance of cavitation under sudden lift

From the high speed images it could be seen that cavitation always occurred during the needle lifting process and the cavitation disappeared before the needle reached the maximum lift position and cavitation was not seen during the closing of the needle. The results obtained with the (moving needle) are very contrary to the previous results of the steady state needle lift conditions. In all the steady state needle lift positions the

cavitation came from the right hole exit, but in this condition the cavitation came into the nozzle from the left hole exit and travelled to the sac and through the right hole to its exit. Figure 8 shows the high speed images under needle upward motion. Due to high framing rate the needle upward motion cannot be explicitly seen as the time between two images are too short. No cavitation was initiated in Figure 8 (a), but in the subsequent images Fig. 8 (b), (c) and (d), it could be sent that a bubbly string of cavitation entered from the left hole. These strings of cavitation followed the axis of the hole and were travelling against the flow. In Fig. 8 (e), it could be seen that the cavitation reached the entrance of the left hole and further travelled into the sac and into the opposite (right) hole and continued its way to the hole exit, Fig. 9 (f) - (i). The cavitation phenomenon observed under the needle motion was similar to that of the intermittent cavitation. The appearance of the bent profile in the sac was associated with the oscillating characteristics of the cavitation as described in the earlier section. Similarly the cavitation became bubbly and broke-off at the boundaries between sac hole and holes as observed in the previous conditions.

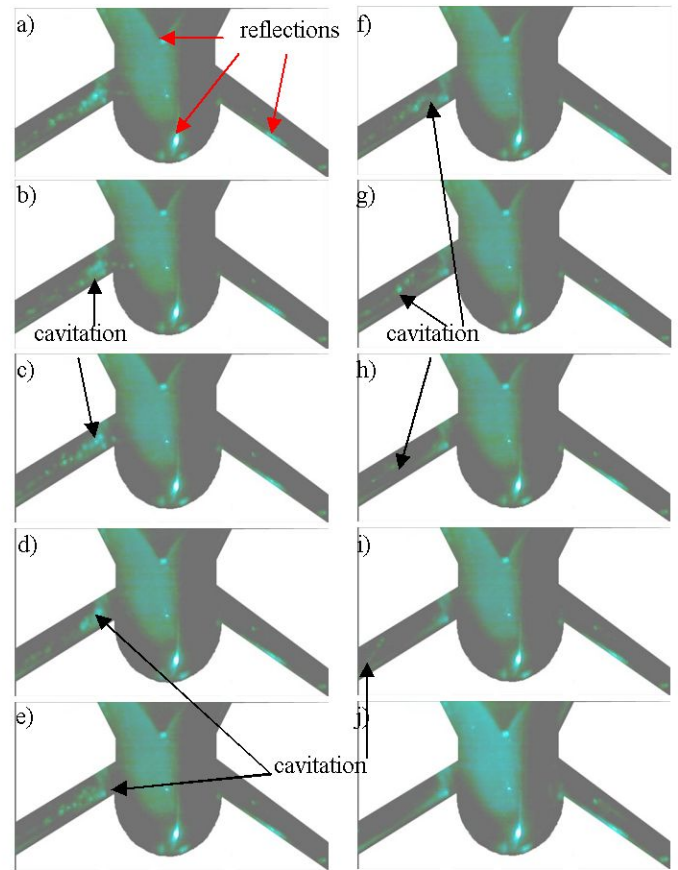


Figure 9 – Disappearance of cavitation under sudden needle lift

Regarding the disappearance of cavitation, there were some differences between this situation (moving needle) and the case discussed under fixed needle lift positions. The overall phenomenon of disappearance of cavitation under needle motion seems to be completely different. As shown in Fig. 9 (a), the string became very thin in the sac hole and few traces of bubbles were still seen in the right hole, but still thick cavitation was present in the left hole as shown in Fig. 9 (b), (c) and (d). Under these conditions there was no motion of cavitation from the left hole into the sac. The bubbly string in this part of the nozzle became gradually thin and disappeared within the left hole as shown in Fig. 9 (e) to (i).

In the first part of this paper the flow rate and the needle lifts were maintained constant, but in this section the flow rate was maintained constant but the needle was moving. The flow phenomena in the nozzle sac under needle motion are completely different compared to a fixed needle position. The sudden movement of the needle caused a drop in pressure and a strong flow recirculation zone under the needle. These low pressure and re-circulating zones induces a strong counter rotating vortex in the sac, which brings cavitation from the left exit of the hole. But under fixed needle lift position, the vortex created under the needle in the sac caused the cavitation to come from the right hole exit.

CONCLUSION

This study shows that cavitation is very unsteady and it is very sensitive to small perturbations due to the flow, geometry and the eccentricity of the needle. Two types of cavitation structures (intermittent and continuous) were observed under steady state flow and constant needle lift positions. Under fixed needle lift positions and under all flow conditions the intermittent cavitation always originated from the right hole and travelled against the flow into the nozzle sac volume and into the left hole and to its exit. The global profile of intermittent cavitation was similar to continuous cavitation, which was hanging in the sac and linking two holes. Under constant needle lift conditions the cavitation always disappeared in the nozzle sac. But under transient operation of needle motion, the intermittent cavitation was always observed during the needle lifting process and the cavitation disappeared before the needle reached the maximum lift position. Unlike steady state needle lift positions the cavitation travelled in the opposite direction from the left hole exit to the sac and from the sac to the right hole exit. Under this condition, the cavitation disappeared in the hole. The flow and cavitation structures prevailing in the nozzle sac and the nozzle holes under needle motions are very different compared to the case of constant needle lift positions.

AKNOWLEDGEMENTS

The authors would like to acknowledge the contribution made by Xi P in the fabrication of the optical nozzle.

NOMENCLATURE

Symbol	Quantity	SI Unit
A	Orifice area	m ²
d	Nozzle hole diameter	m
Q	Water flow rate	m ³ /s
Re	Reynolds Number	
V	Average velocity of the flow	m/s
μ	Dynamic viscosity of water	kg/m s
ρ	Density of water	kg/m ³

For water at 20°C and under atmospheric pressure the density and the dynamic viscosity are taken as : $\rho = 1\,000\text{ kg/m}^3$, $\mu = 1.00 \times 10^{-3}\text{ kg/}$.

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