ILASS 2008
Sep. 8-10, 2008, Como Lake, Italy

Paper ID ILASS08-1-12

VISUALISATION OF STRING CAVITATION FORMATION AND DEVELOPMENT INSIDE TRANSPARENT INJECTOR NOZZLE REPLICAS

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ABSTRACT

The formation and development of string cavitation inside transparent replicas of injectors used with large 2-stroke Diesel engines is visualized using a high speed camera. Single-hole nozzles with cylindrical and converging tapered holes are utilized. Flow images indicate that elongated two-phase flow structures are formed either from pre-existing cavitation sites of from outside air trapped in the core of recirculation zones persisting up to the exit of nozzle holes. These elongated air/vapour structures are termed as string cavitation. Their appearance and further development is recorded as function of the operating conditions while mean images revealing the probability of finding a string at a particular location inside the injection hole is deduced.

INTRODUCTION

Cavitation in fuel systems for modern high-pressure automotive, power generation and marine Diesel engines is known to initiate at flow areas with sharp corners where the pressure may locally drop below the vapour pressure [1-5]. This leads to the formation and further growth of cavitating structures which usually survive up to the nozzle hole exit and promote fuel atomisation [6]. However, some studies [7] have indicated that cavitation can be also associated with hole-to-hole and cycle-to-cycle variations. Although geometric-induced cavitation is a relatively well-known phenomenon not attributing significantly to those cyclic spray variations, another form of cavitation has been identified recently as a possible flow mechanism responsible for those instabilities. This is referred to as 'string' or 'vortex' type cavitation [8-10]. These cavitation structures are found usually in the bulk of the liquid, in the area where vortical structures exist. Although different studies have shown similar behaviour in various types of multi-hole nozzles, their formation process has been found to be relatively irregular while their interaction with the mean flow is still poorly understood.

The present paper represents a continuation of the work presented recently in [10, 11] and investigates the formation of string cavitation in Diesel injectors for large two-stroke Diesel engines. In order to focus on the cavitating flow structures forming inside the nozzle, the geometry has been simplified to a single-hole one, as shown in Figure 1. Visualisation has been achieved by manufacturing fully transparent nozzle replicas, which have provided optical access inside the nozzle volume upstream of the injection holes, inside them as well as at the sprays formed at the nozzle exit. Image collection over sufficient duration period has provided information on the string frequency of appearance and life time.

The nozzle designs tested have included cylindrical as well as tapered holes converging towards the nozzle exit. Focus in the present paper is placed on characterising the various flow regimes related to the formation and development of string cavitation.

The next section of the paper describes the test cases investigated. Since detailed description of the test rig is well documented elsewhere, example in [8], no further details are presented here. Then the various results obtained are presented while the most important findings are summarised at the end.

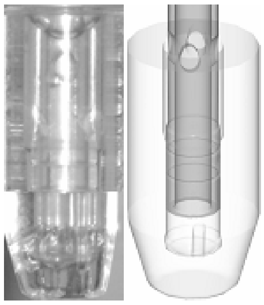

Figure 1: Nozzle geometry investigated

DESCRIPTION OF TEST CASES

Table 1 summarises the range of operating conditions investigated for the visualisation studies. The nozzles used were made to real-scale (1:1); the nominal injection hole diameter of the real-size nozzle is about 1.5mm and the needle lift at its full (stop) position is about 3.7mm. As mentioned, both cylindrical and tapered injection holes have been made. Cylindrical holes with sharp inlet corners promote formation of geometry-induced cavitation, while tapered holes (i.e. holes with conical shape converging towards the nozzle exit) suppress or even eliminate formation of cavitation at the hole inlet. The flow conditions refer to cavitation numbers between 1 and 7, which is similar to those of the real-size injector operating under nominal engine running conditions. However, the much lower injection pressures used restrict the experiment into flow rates (and Reynolds numbers) much lower than those of the real operating conditions. Since the fuel flow through the injector nozzles, especially through the holes, is highly turbulent, all flow features can be expected to behave transiently and with short time-scales. The Photron FASTCAM-ultima APX cameras were used with a frame rate between 6,000 to 16,000fps; this was considered sufficient to capture the temporal development of cavitation using a shuttering time of 30μs. In total 3000 to 12,000 images were collected for a particular case. Furthermore, superimposing of images has allowed for time- and spatial averaging over the whole nozzle volume depth of the projected 2-D images. Imaging was performed for various combinations of the cavitation and Reynolds number and for different needle lifts. The case to be reported here correspond to the 'full' lift, which is defined as the nominal stop position of the needle in the real injector. The 'low' lift case corresponds to a needle lift at about 80% of the full one. In this case, the slide is just uncovering the injection holes. Finally, the 'high' lift case corresponds to 120% of the full lift position. Finally, for most of the cases to be presented here, the cavitation number has been kept constant at CN=4 and the Reynolds around 60,000 unless it is stated otherwise.

Nozzle Design	Needle Lift	Injection Pressure [bar]	Flow rate [l/s]	CN Number	Re Number
Single Hole Cylindrical	Low, nominal & high	2 to 8	0.12 to 0.24	1 to 7	49,400 to 88,250
Single Hole Tapered	nominal	3 to 5	0.18 to 0.25	1 to 4	70,600 to 92,000

Table 1: Operating conditions for all presented investigations

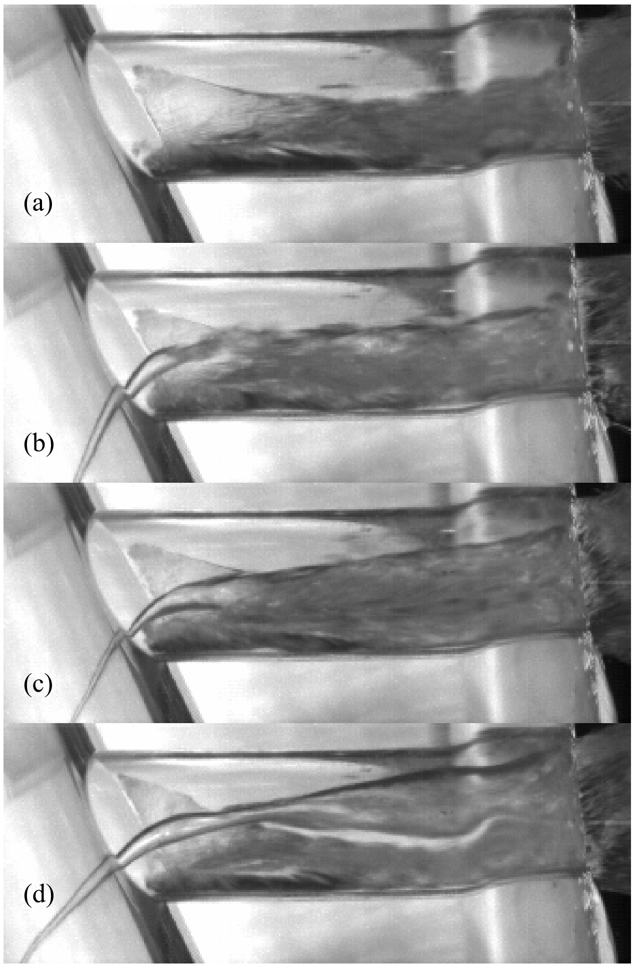

Figure 2: Images showing four distinct cavitation patterns inside the injection hole of the single-hole cylindrical nozzle, a) only geometric cavitation, b) string cavitation at the lower part of the injection hole, full mixed with geometric cavitation, c) string cavitation at the center of the hole, partially mixed with geometric cavitation and d) string cavitation at the upper part of the injection hole, string cavitation separated from geometric cavitation *[CN=2, Re≈53,000]*

RESULTS & DISCUSSION

Cavitation regimes in the cylindrical-hole nozzle

Due to the specific characteristics of the nozzle geometry investigated, geometric-induced cavitation is forming at the lower part of the injection hole and stays attached to its bottom surface up to the nozzle exit. This can be clearly seen in Figure 2a, corresponding to the nominal needle lift and a cavitation number equal to 2; this number is sufficient enough for fully developed cavitating conditions to be reached. It has been observed that in addition to the geometric-induced cavitation, vortex or string cavitation is also forming even in this simplified nozzle geometry; typical images of that can be seen in Figure 2a,b and c. Cavitation strings are developing upstream of the entry to the injection hole well inside the nozzle's sac volume and extend up to the nozzle exit. Their formation and life time varies with the operating and flow conditions (i.e. needle lift, Reynolds and cavitation numbers); more details will be presented in a following section of the paper. At this point, it is worth noticing that the development of string cavitation inside the injection hole can be found in three distinct locations relative to the cavitation cloud present at the bottom of the injection hole. As the three last images of Figure 2 reveal, string cavitation can be mixing fully with the geometric hole cavitation (Figure 2b), being clearly separated and flowing above it (Figure 2d), or found near to its boundary and thus been partially mixing with it (Figure 2c). It is also worth noticing that, depending of the area of its development, the flow conditions at the hole exit cross sectional area are greatly modified since in the first case the upper part of the injection hole is occupied by liquid while in the last case it is occupied also by cavitation bubbles.

Cavitation formation in the cylindrical-hole nozzle

In this section, sequence of high speed images revealing the formation process of geometric and string cavitation inside the cylindrical hole nozzle are presented. Two operating conditions have been selected. The first one corresponds to low cavitation number where bubbles are just start forming while in the second, a fully developed cavitation cloud at the hole bottom exists; these can be seen in Figure 3 and Figure 4, respectively.

Concentrating first on the low CN number case, one can seen cavitation bubbles rarely forming at the bottom edge of the hole inlet and transported towards the hole exit; this is the so-called incipient cavitation regime. At some time instances, highlighted with a circle superimposed on the images, an elongated and rather large bubble structure appears to travel in the direction opposite to the main hole flow. This is forming and collapsing a few times until it may become a long cavitation string structure propagating well inside the nozzle's sac volume; its life time is only a fraction of the ms.

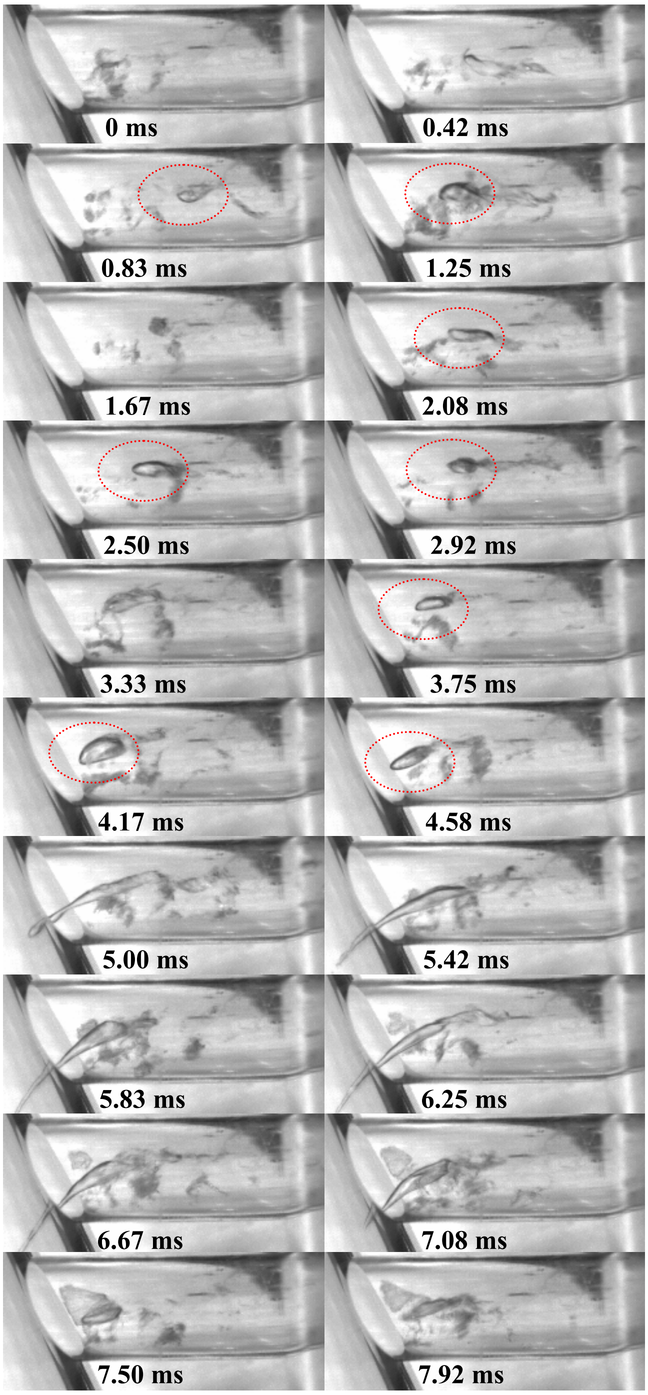

Figure 3: Sequence of high speed images showing the formation of string cavitation inside the single-hole cylindrical nozzle at low cavitation number [*CN=1, Re≈53,000*]

A similar flow behavior is realized with increased Reynolds and cavitation numbers; this can be seen in the following Figure 4. Although the mean hole liquid velocity is expected to be higher in this case, it seems that the cavitation string again propagates in the direction opposite to the hole flow while it appears to originate either from the hole exit or from its mid distance between the inlet and the exit. Once formed, it is not possible to distinguish any motion towards or upwards the hole exit. However, on the other side of the hole inlet, initially the string is moving inside the sac volume but at later stages its movement reverses its direction and moves towards the injection hole exit. In the area close to the hole inlet, the two cavitation structures are clearly separated while they mix around half hole length.

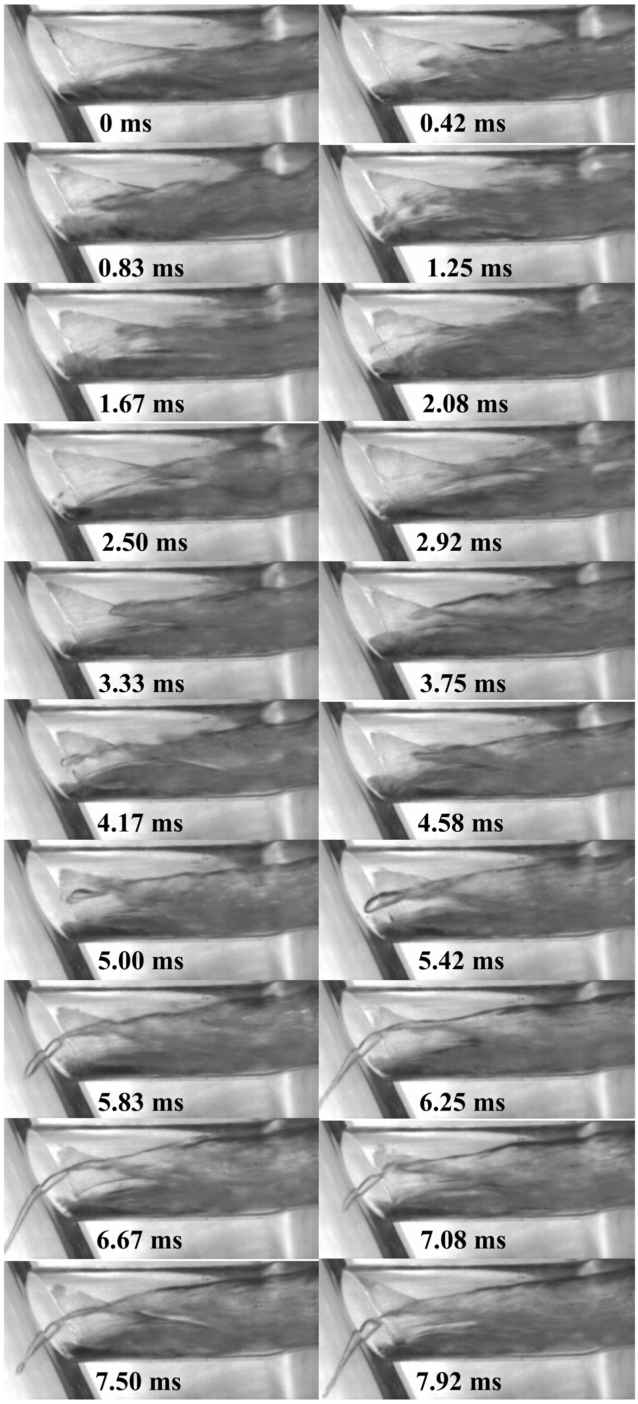

Figure 4: Sequence of high speed images revealing the formation of string cavitation inside the cylindrical single-hole cylindrical nozzle at nominal cavitation number *[CN=4, Re=70,600]*

Cavitation formation in the tapered-hole nozzle

The area of formation of cavitation strings raises some questions since they appear to develop in the direction opposite to the hole flow. Relevant recent findings in this area suggest that cavitation strings develop inside vortical structures present in the flow [10]. Furthermore, they have been found to originate from pre-existing cavitation sites. It was thus interesting to observe string cavitation forming in the tapered hole nozzle which is geometric-cavitation free. Representative post-processed images of the temporal evolution of string cavitation for the tapered-hole nozzle are shown in Figure 5 and Figure 6; these correspond to two different cavitation numbers of 2 and 4, respectively.

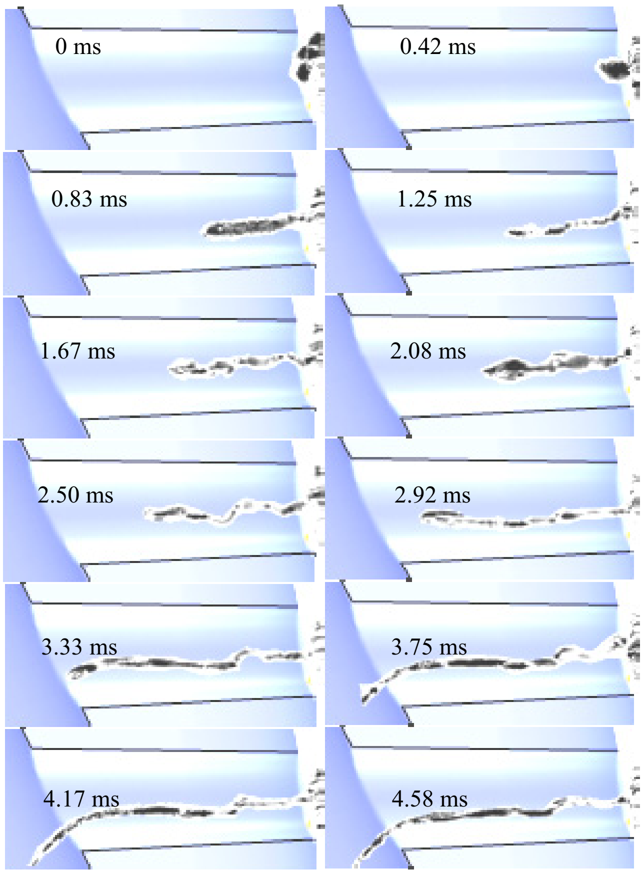

Figure 5: Post-processed high speed images revealing the formation of string cavitation inside the tapered single-hole nozzle *[CN=2, Re=70,600]*

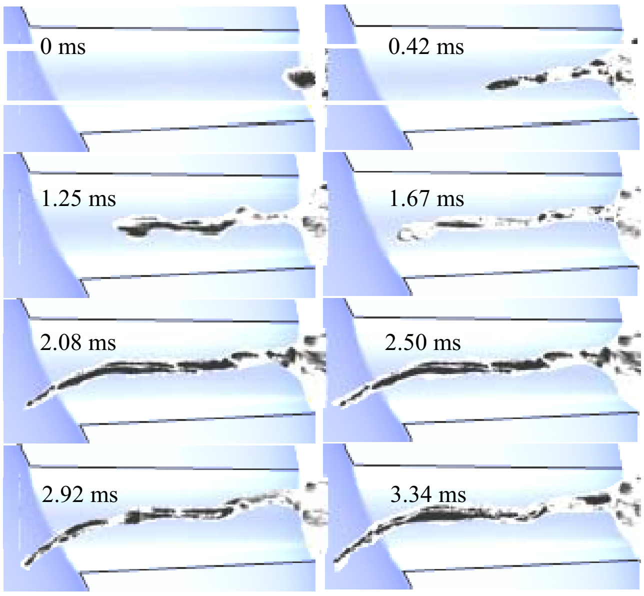

Figure 6: Post-processed high speed images revealing the formation of string cavitation inside the tapered single-hole nozzle at increased cavitation number *[CN=4, Re≈92,000]*

The images indicate that due to the vortical flow present inside the injection hole (described in more detail in [11]), cavitation strings may initiate from downstream air, trapped in the low pressure region present up to the hole exit and propagating upstream inside the nozzle hole; a similar and well known case is that of the air-core surrounded by liquid film at the hole of pressure-swirl atomisers. Comparison between Figure 5 and Figure 6 reveals faster formation with increasing cavitation number. In the next section, the frequency of appearance and area of formation/development are quantified for the range of operating conditions tested.

Quantitative string cavitation characterisation

In this section, results obtained from post-processing of the acquired images are presented. Initially, it has been considered useful to elaborate more on the tapered-hole nozzle, where, more clear images have been obtained in the absence of geometric-induced hole cavitation. The result of Figure 7 shows the time-averaged probability of finding cavitation string in a particular location inside the injection hole. There is clear indication that the string is rather stable with respect to its location inside the injection hole. The frequency of appearance is again about 50% over the whole hole length while it decreases significantly upstream of the injection hole entry. Effectively, this implies that ~50% of the time strings are present while 1/5 of them manages to enter inside the nozzle's sac volume, as the light-blue values on the colour scale of this plot indicate.

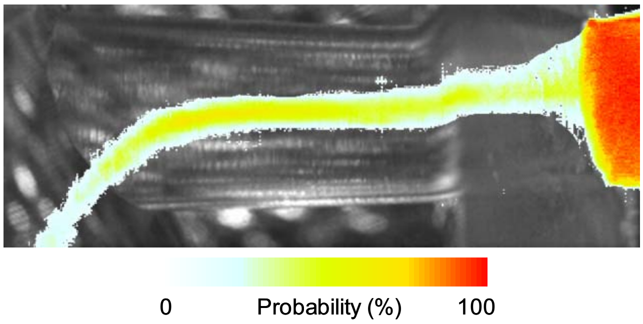

Figure 7: Spatial probability of string cavitation location inside the tapered single-hole nozzle *[CN=2, Re=70,600]*

Unfortunately, it has not been possible to produce mean images for the cylindrical hole nozzle. A kind of similar information though with respect to the appearance of cavitation strings inside the injection hole and the sac volume has been obtained with the air of the following Figure 8.

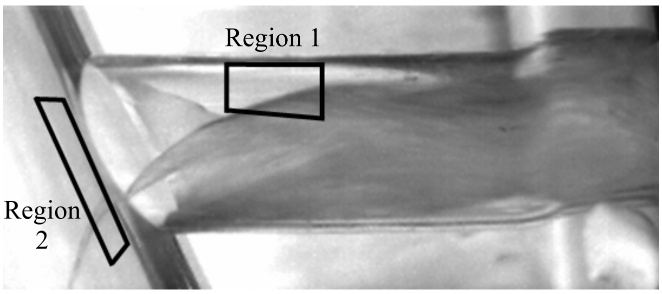

Figure 8: Regions for string cavitation detection presence inside the injection hole (region 1) and inside the nozzle's sac volume (region 2)

This figure shows a representative image of the cavitation pattern where both hole and string cavitation co-exist. Since the cavitation string appears and disappears, it has been considered useful to capture the temporal evolution of its formation at two distinct locations indicated as 'Region 1' and 'Region 2', respectively, in Figure 8. The former one indicates the presence of a cavitation string inside the injection hole while the latter one indicated the presence of the cavitation string inside the nozzle's sac volume.

Corresponding results are presented in the last two Figure 9 and Figure 10; the y-axis on these graphs takes only two values of 0 and 1 indicating the presence or absence of the cavitation string from the area of interest, respectively. In Figure 9 results are plotted for three different cavitation numbers by keeping the same needle lift while in Figure 10 results reveal the effect of needle lift by keeping the same cavitation and Reynolds numbers; for both figures, the top row refers to 'Region 1', i.e. inside the injection hole while the bottom row to 'Region 2', i.e. inside the nozzle's sac volume. It is interesting to notice that increasing cavitation number results to continues presence of the cavitation string inside the injection hole. Its appearance inside the sac volume is also enhanced with increasing CN (or equivalent, flow rate) conditions. On the other hand, it seems that the increasing or decreasing needle lift plays a less important role to the presence of string cavitation both inside the sac volume and the injection hole.

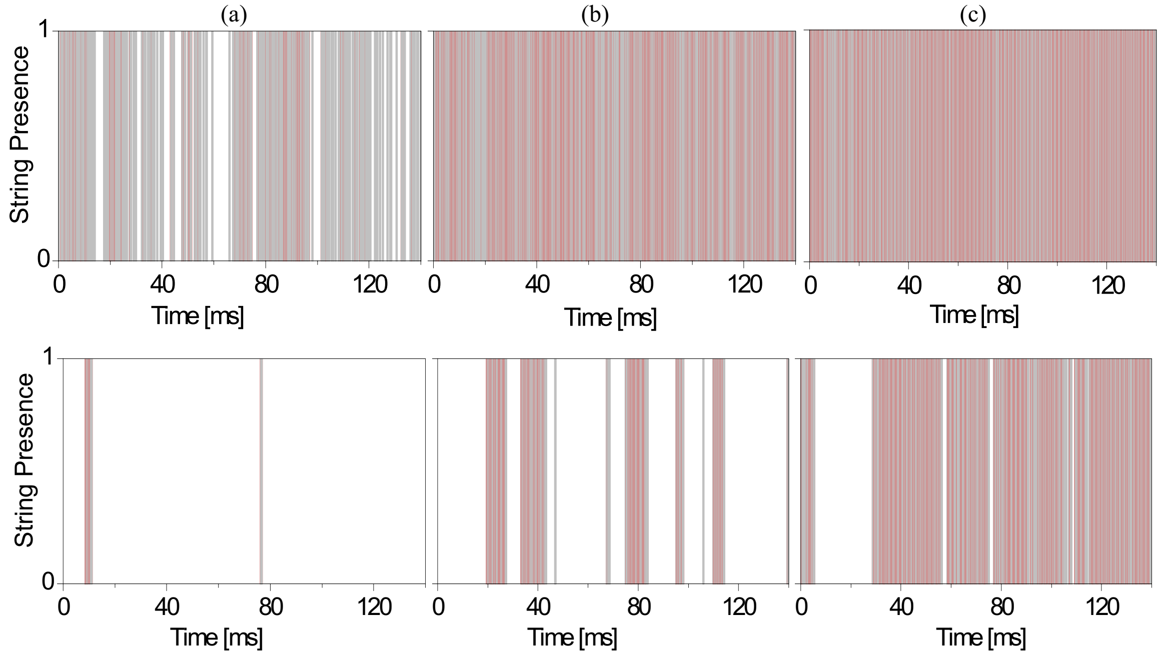

Figure 9: Effect of cavitation number on string appearance sequence for the cylindrical single-hole nozzle at high needle lift (a) *CN=1, Re=49,400, (*b) *CN=2, Re≈52,950* and (c) *CN=7, Re=88,250.* Top row corresponds to region 1 and bottom to region 2 of Figure 8, respectively.

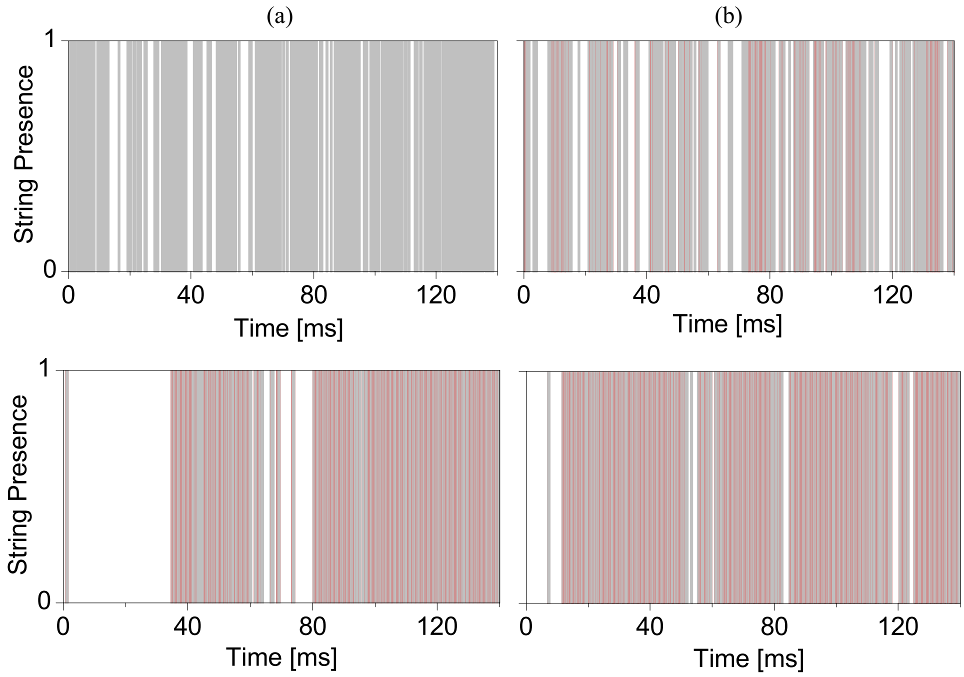

Figure 10: Effect of needle lift on string appearance sequence for the cylindrical single-hole nozzle at nominal cavitation number (a) *CN=4, Re=70,600, nominal lift* & (b) *CN=4, Re≈67,000, low lift.* Top row corresponds to region 1 and bottom to region 2 of Figure 8, respectively.

CONCLUSIONS

The present paper represents a continuation of past work of the authors, investigating the formation and development of string cavitation inside transparent replicas of injector nozzles used with large 2-stroke Diesel engines. Focus is placed on single-hole nozzles with cylindrical and converging tapered holes which allow for clearer optical access compared to multi-hole nozzles, while at the same time, they are free of hole-to-hole interactions. Flow images indicate that elongated two-phase flow structures, termed as string cavitation, can be formed from outside air trapped in the core of recirculation zones persisting up to the exit of nozzle holes. The formation of cavitation strings is enhanced with increasing flow rate (and thus increasing cavitation number) while it is less sensitive to needle lift. Cavitation strings may travel upstream the injection hole entry well inside the nozzle's sac volume but with a reduced frequency of appearance compared to their presence inside the injection hole.

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