

Real-Size Real-Shape Real-Pressure Transparent Nozzles to contribute to Nozzle Design and Cavitation Control for GDI

A. Agresta¹, J. Hélie^{*2}, E. Kull³, N. Lamarque², A. Lyubar³, S. Schuster³

¹CPT, Pisa, Italy

²CPT, Toulouse, France

³CPT, Regensburg, Germany

*Corresponding author: Jerome.helie@continental-corporation.com

Abstract

A proof of concept of a real-size, real-shape, real-pressure, representative surface roughness, transparent nozzles is demonstrated in the present paper that can be used with Design of Experiments to investigate geometry influences on flow, cavitation and spray. The nozzle is mounted on an actuated valve. It contains an angular portion of a real nozzle, including the needle-body area, the sac geometry, the hole geometry and the external nozzle shape. The working fluid can be chosen to represent a real fuel, or for basic studies n-heptane.

Wide view pictures return the penetration curve. Close-up visualizations are realized in liquid-into-air and liquid-into-liquid configuration and are compared. Shear and string cavitation phenomena are observed. A strong effect of the conicity is seen but the possible presence of hydraulic flip is not found to affect the overall occurrence of cavitation in the high fuel pressure conditions.

Keywords

Transparent nozzle, cavitation, spray, multihole, atomization

Introduction: Benefit and limitation of transparent nozzles up to now.

Transparent nozzles have been used for years to allow optical measurements of in-nozzle cavitating flow in order to avoid erosion and to master the effect on atomization. Until now, transparent nozzles were typically used mostly in simplified conditions. Initially the nozzles were enlarged for easiness, with similarity of Reynolds, Weber and cavitation numbers. The hole entrance conditions were found to influence the secondary flow and then the cavitation development [1]. Sometimes also the authors took advantage of large-scale injector configurations to investigate marine diesel engine applications. In this way a reduced pressure, complex and quasi real shape was possible to be reproduced [2]. However, as cavitation is a multiscale effect due to bubble growth from nuclei sizes, cavitation cannot be scaled up [3]. Even if some advantages exist with a higher image resolution thanks to enlarged holes, the results are still questionable: are they represent correctly the nucleation – bubbling – pockets(clouds) transitions and how is it influencing the general behaviour including atomization? The first realization of real size nozzles was a great step toward a more representative transparent nozzle which compares good to real parts.

Simplified realistic size 2D holes were initially considered [4] and are still useful for basic simulation model validation or well-controlled optical measurements [5]. It was found that visualisations are more sensitive than mass flow rate measurement [6]: cavitation inception occurs prior to the change in mass flow rate, and bubbles are observed in the spray area even without full mass flow rate collapse (choked flow). The hole inlet radius was identified to greatly influence the cavitation inception and the flow detachment at the hole inlet edge as the flow's direction turns toward the hole [7]. The cavitation length increases with the pressure difference, and lastly, the role of the cavitation collapse for the specific conditions of a collapse at the vicinity of the hole exit was identified to improve the atomization [8]. At higher cavitation number conditions, when the cavitation zone is reaching the hole exit, the air can propagate back in the gaseous area, substituting to the vapor, stopping cavitation and stabilising this gaseous area. This so-called *hydraulic-flip* is reducing the atomization intensity and is stabilizing the flow [4,7,8].

The limit of 2D holes are driven by the 2D cavity depth: if too small the channel will undergo boundary because of the walls presence, with corner recirculations and square section flow profile development. If too deep, the shadowgraphy visualisation is integrated along the whole optical path and is the result of a superimposition of multiple bubbles developing at different depths. The signal absorption saturates even with low density of cavitation and in moderate regimes. It is then almost impossible to distinguish different vapor density levels. It is thus useful to use more complex X-Ray measurement [9]. Another aspect which cannot be fulfilled by 2D nozzles is the fluid velocity at needle seat and towards the sac geometry as found in real nozzles. The reason is that the flow area along the flow line is usually becoming smaller due to the conical geometry around the seat and SAC which cannot

be represented in 2D. Many authors investigated central axisymmetric holes that are more realistic in terms of geometry scale. However, visualisation of axisymmetric holes is also difficult. More importantly, in central 2D channel or axisymmetric holes, the fluid is cavitating uniformly with a stable behaviour, whereas the observed regimes of asymmetrical nozzles with non-divergent holes are mostly unstable. For instance, supercavitation is not stable. Therefore, asymmetrical inlet conditions [9] and inclined holes [7] were then studied.

Cavitating vortices (string vortices) were also observed [1,2], similar but not identical to the tip cavitating vortices observed in the flow over hydraulic machines blades [10]. The subject of the development process of the cavitating vortices is still unclear: they can emerge from entrapped bubbles in the core of the fluid volume, from the sac area and from the exit area with air content.

Recent publications report building and measurements of a realistic shape of transparent nozzles using one simple rectangular insert with the flow hole inside. Some authors succeeded to integrate it in a real metal nozzle [11], or to produce an even more complex shape fully transparent [12]. However, keeping the nominal geometry or managing a complex shape when considering real-size nozzles and high-pressure conditions becomes very difficult. No real proof of concept of realistic nozzles that are exhibiting the former qualities while being at the same time compatible with rapid prototyping approach has been demonstrated until now to our knowledge.

Due to the limited size of the current paper, the effects of the cavitation on atomization will not be listed in detail, but the literature content in this domain is already impressive even if many effects remain unclear in 3D cases. Moreover, most of the completed work has been done for Diesel application, which means that the length-over-diameter is typically larger than 5, where it is much smaller in Gasoline Direct Injection.

The present paper proposes a concept of transparent nozzles that matches the previous constraints. A proof of concept of a real-size, real-shape, real-pressure, representative surface roughness, transparent nozzles is demonstrated in the present paper that can be used for Design of Experiments. The design proposal and summary of the accomplished work is listed in the first section. The operating conditions and measurements are described in the second section. The results are shown in the third section.

Axisymmetric and real-shape designs

The first basic investigations used an axisymmetric design (**Figure 1**). The spray results discussed later in this paper will prove the needs of the real-shape designs to get results comparable to real GDI nozzles.

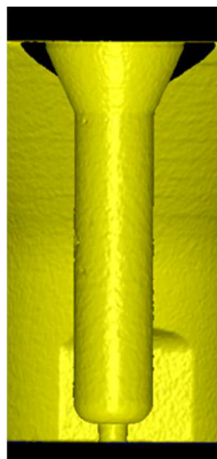


Figure 1: XCT of axisymmetric design with spray hole diameter (D_{in}) of 200 μm

The manufacturing technique used here easily allows designs variations. The influence of design on maximum stress was investigated using Finite Element Analysis (FEA). A radius inside the glass part was set to different values and the influence is visible in the calculation (**Figure 2**). Correlation with burst tests gave the limit to be applied to design new glass nozzle geometries which are very near to real GDI nozzles.

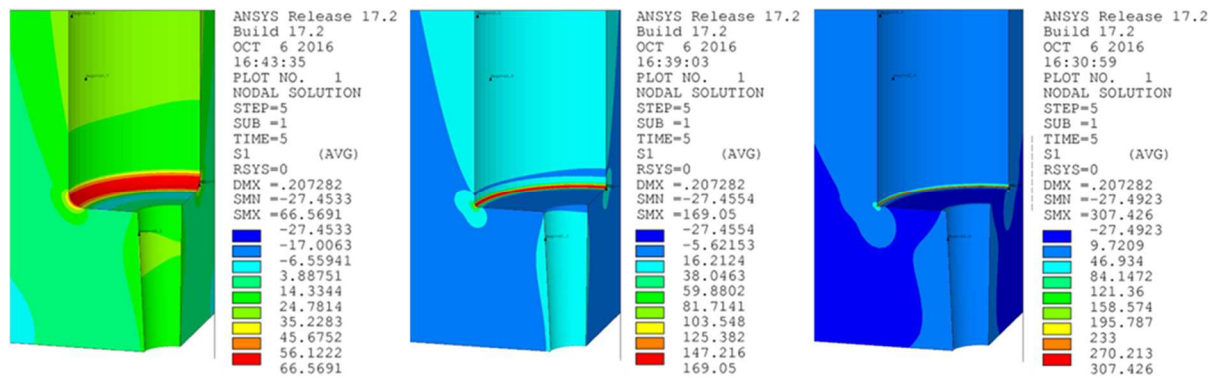


Figure 2: FEA results showing influence of radius variation on stress level

To realize samples with a real shape, a 3D sector is taken out of the real nozzle flow volume including also the valve part which is typically spherically shaped. It contains an angular portion of a real nozzle, **Figure 3**, including the needle-body area, the sac geometry, the hole geometry and the external nozzle boundary. Quartz glass (fused silica) is used and laser-etched manufacturing has been selected.

The fixed lift is 85 microns, with a $\pm 4 \mu\text{m}$ measured difference between the configurations. It corresponds to the minimum axial distance between the upper and the lower spherical shapes. To be actuated, the geometry contains an upstream hole connection, **Figure 3**, to a valve that is placed on the upper part. Therefore, the sample is more representative of a fully opened nozzle, quasi-steady condition, but also can be actuated to generate a modelled transient, for instance to measure spray penetration.

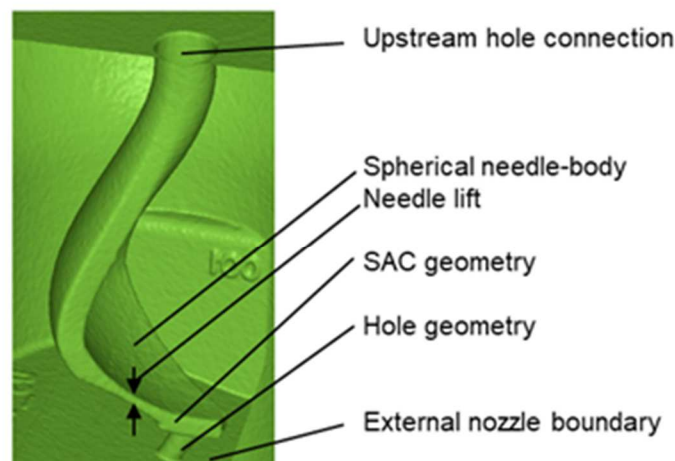


Figure 3: flow volume incorporated in a glass cylinder

The geometry is controlled using XCT (Werth TomoScope). As XCT is known to be weak to capture sharp edges at full resolution, a microscope is used to quantify the hole edges rounding which is found to be sharp (rounding radius less than 1 micrometre). The surface roughness obtained by both techniques typically returns an average roughness equal or smaller than 3 microns. These two parameters (edge sharpness and surface roughness) are important for the cavitation development and they correspond here to the same values as measured on metal nozzle with holes that are drilled by micro erosive technique (EDM). Typical XCT measurements can be found in **Figure 4** and the design values confirmed by XCT are presented in **Table 1**.

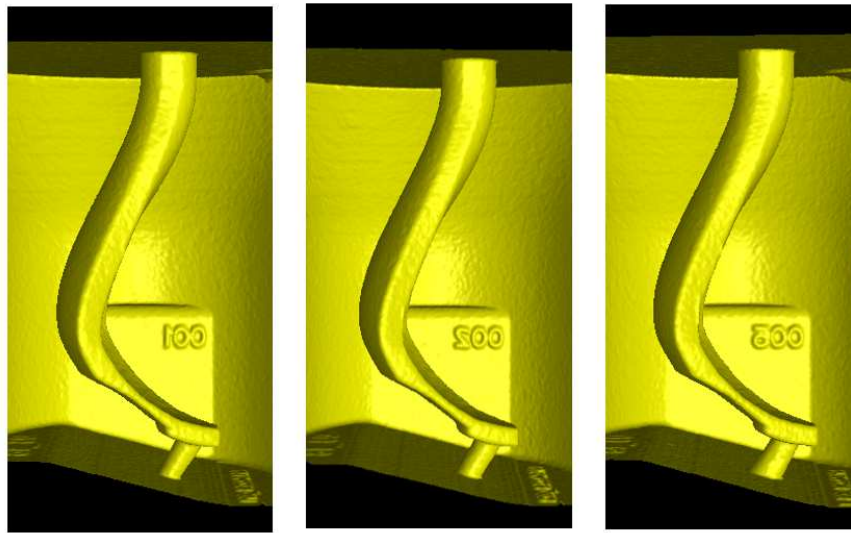


Figure 4: From left to right: XCT measurements of geometry #1,#2,#5

Table 1. Flow hole geometry dimensions in mm

geometry	D_in	D_out	CF	Hole length L
#1	0,18	0,15	10	0,29
#2	0,18	0,17	3	0,29
#5	0,19	0,22	-10	0,29

The conicity factor of a spray hole is calculated as:

$$CF = \frac{(D_{in} - D_{out})}{L * 100}$$

Experimental set-up

The working fluid can be chosen as representative of a real fuel, and for simplicity N-heptane is chosen here. In the present results, the inlet fuel pressure can be varied while keeping or varying the exit surrounding pressure to atmospheric. The fuel supply is obtained using a low-pressure electrical pump, a cooling exchanger, a high pressure pump (CPT), a common rail to damp oscillation, a fuel supply line with a pressure sensor (Kistler) to the injector-valve followed by the tested transparent nozzle.

Shadowgraph pictures are realized using a long-range microscope (Navitar with home-made tubes from RDvision). A half-inch flexible fibre optic light guide mated with a powerful LED illuminator (white steady light). Videos were made with a high-speed video camera (Phantom V1210). The fast camera was used at 30Khz image rate with a exposure time of 2 microsecond. Motion blur effect has no relevance when time-averaging is finally done. A medium resolution is typically used in order to have simultaneously the in-nozzle flow and the spray. A small optical distortion is typically visible at the spray hole exit and the spray appears as shifted to the right.

For image processing, an open-source java software is programmed (ImageJ-Fiji), with algorithms as: background-subtraction, median filtering, binarization, and mathematical morphology (specially to fill holes or connect some parts) and finally connected zone identification / labelling to measure sizes, angles, areas etc. The near angle definition is defined as the external angle on 5 hole-diameter length after the hole exit. It uses a threshold level of 5% intensity by averaging during 2ms the binarized images

Results for an axisymmetric design

The axisymmetric design with good optical accessibility enables to see cavitation phenomena and spray break up at the same time without any optical hindrances. Such a design, as in **Figure 1** can be easily finally tested up to 200 bar. Pressure variation from 0.5 bar to 2 bar relative fuel pressure **Figure 5**, show that for 0.5 bar the back pressure is too high for cavitation at the inlet edges. At 1 bar relative pressure the cavitation starts to become visible at the inlet edge. At 2 bar the cavitation is strongly developed and enables a stable hydraulic flip as is shown in **Figure 5**.

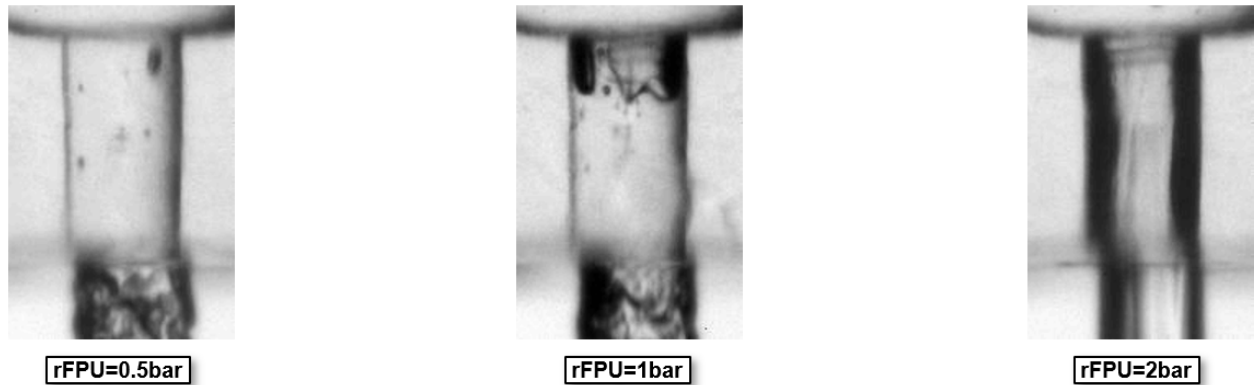


Figure 5: Onset of cavitation which leads to a hydraulic flip with increase of relative fuel pressure (atmospheric air conditions)

Going to higher inlet pressures of 50 bar is shown in **Figure 6**. With an increase of backpressure from atmospheric to 9 bar cavitation decreases and the hydraulic flip suddenly vanishes. Further increase of backpressure up to 31 bar reduces the cavitation further more and there is a slight reduction of plume angle.

The cavitation number used is defined by [13]:

$$K^{0.5} = \sqrt{\frac{P_{in}}{P_{in} - P_{back}}}$$

with here $P_{sat} \ll P_{in}$

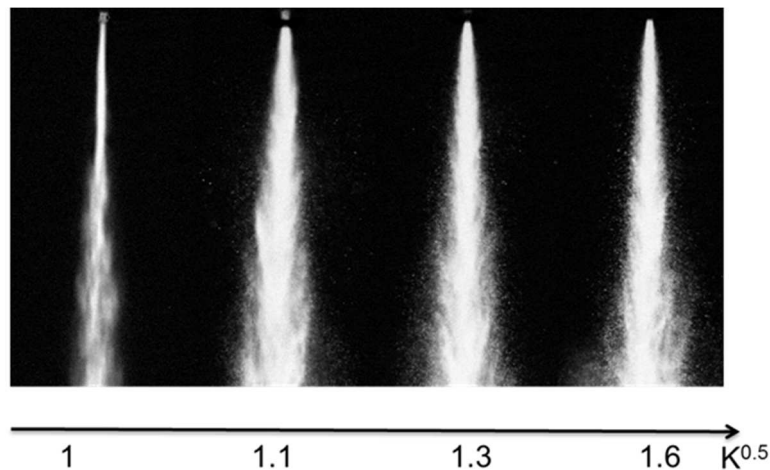


Figure 6: Spray at 50 bar fuel pressure and increase of back pressure from atmospheric ($K^{0.5} = 1$) to 30 bar ($K^{0.5} = 1.6$) air conditions

Figure 7 shows the spray angle vs. cavitation number. The different appearances of hydraulic flip can be correlated with the measured spray angles. These phenomena are valid for steady state conditions. For $K^{0.5}$ equal to unity, a stable hydraulic flip is present. A sudden transition to unstable cavitation and hydraulic flip is observed when increasing to higher values. The exit angle is evolving in consequence with an enlarged angle. At $K^{0.5}=1.3$, the hydraulic flip has disappeared, the cavitation is still unstable, and the exit angle stabilises at a plateau value. At higher pressure $K^{0.5}$ close to 2 which corresponds to over 38 bar backpressure, even the cavitation at the inlet edge is vanishing. Now the exit angle is almost null (1.3°). In such latest conditions, the flow can be in between laminar

and turbulent regimes, as the transparent nozzles are real-size. These results confirm with a real size sample what was found in scale-up conditions by Sou and co-authors [10] for instance.

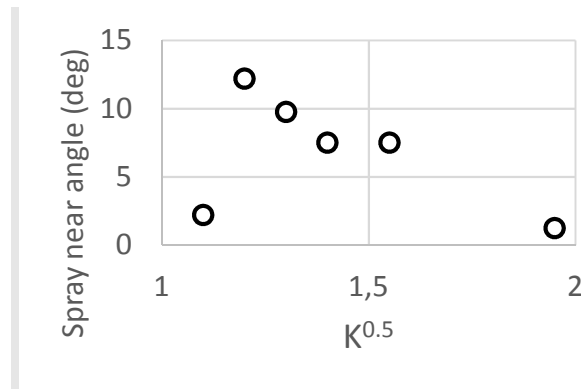


Figure 7: Measured spray angle vs. cavitation number for the measures done

In **Figure 8** fuel pressure is increased to a typical range for Gasoline Direct Injection with a setting of 100 bar. The hydraulic flip is still visible, but downstream in the spray the build-up of a plume angle due to external interactions of the spray with the surrounding air is visible.

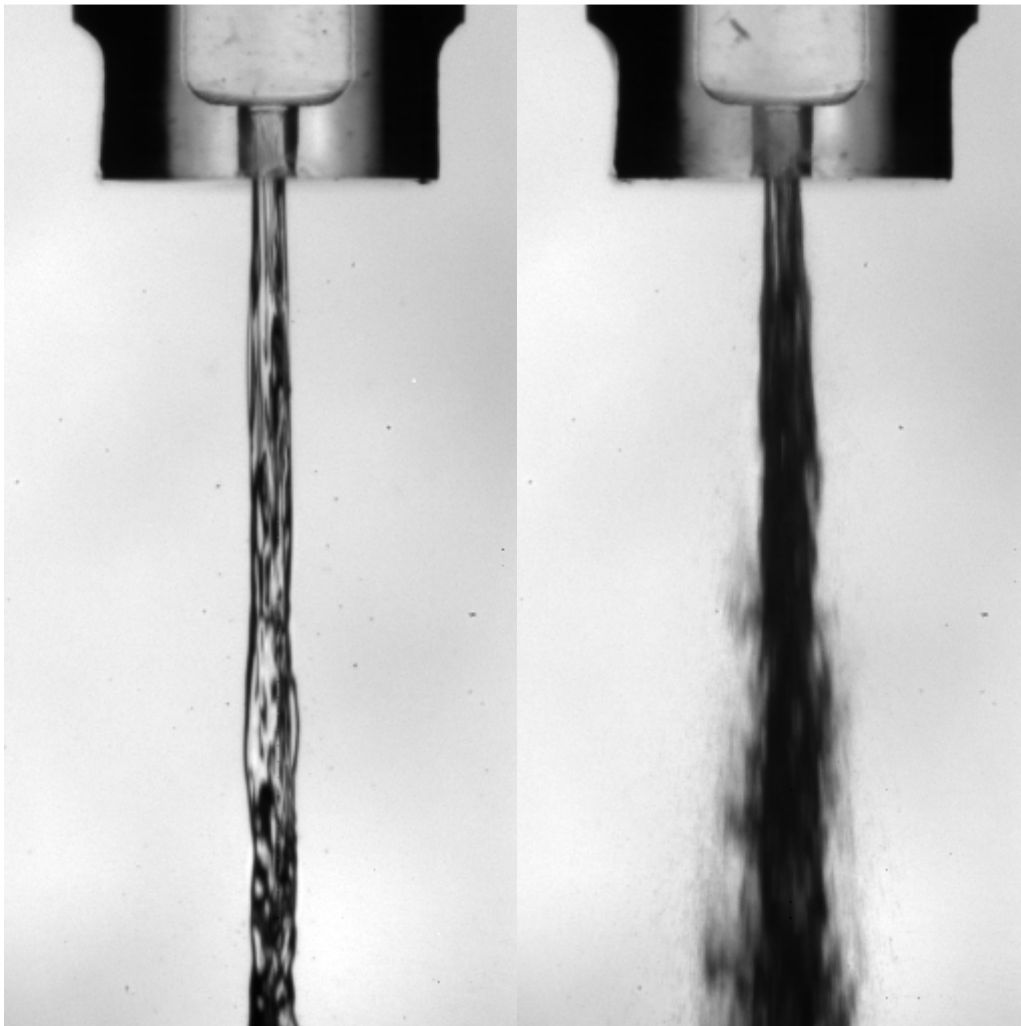


Figure 8: Liquid jet atomization with increase of fuel pressure (10 bar left, 100 bar right upstream pressure) into 1 bar downstream pressure condition.

Results for a real-shape design

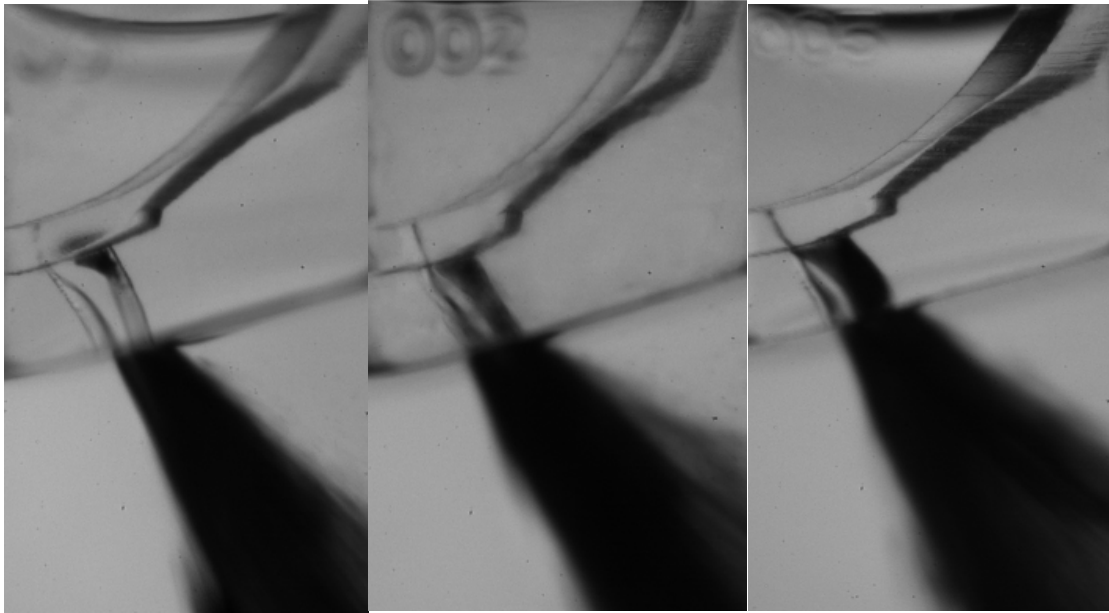


Figure 9. Instantaneous visualisation of in nozzle cavitation and external spray angle at 100bar upstream pressure in into 1 bar downstream condition. From left to right: sample #1, #2, #5

The cavitation pockets and vortices can be observed in Figure 9. The top, dark part in the hole corresponds to the shear zone that is always present. It is partly annular in this round hole and corresponds to the detached flow area (right side). The string cavitation [2] is reaching the upper hole inlet in many cases, being fully continuous or separated in different parts. The cavitating vortices are often attached to the roof (representing the needle limit). Its location can vary from attached to the left zone or to a more central place. With a convergent nozzle, cavitation is largely reduced and even almost cancelled before the hole exit. The flow acceleration and shear generated in the liquid close to the wall enhance the spray exit disturbance. With a quasi-straight hole the shear cavitation zone touches the hole exit, that can slightly enhance the spray angle in one direction with small expelled drops. With a divergent hole the shear cavitation zone extends to a wider area before the hole exit.

Is the cavitation submitted to and conditioned by a hydraulic flip? That would mean air re-entrainment inside the shear or string cavitation that generates a full stabilisation (stable gaseous detached zone) or a slow pulsation (entrainment or air in the vapor area, then area decrease, and then regeneration of vapor area by cavitation, then entrainment of air again etc..). To answer this fundamental question the standard condition of injection into air can be compared to an injection into liquid **Figure 10**. In such a view, the image contrast changes due to the different optical path. After the nozzle, a cavitating jet is visible due to the high velocity of the expelled liquid generating an intense shear force in the surrounding liquid. In **Figure 10**, the cavitation in the hole is not observed to change between the two cases neither with an upstream pressure of 10bar nor with 100bar. At 100bar, the string cavitation is still present. Therefore, the hypothesis of air presence as a key factor of the appearance of a string cavitation is factually rejected. The two main factors that can explain this non-influence of the air presence are: 1) the flow is controlled hydrodynamically by the short turn and the flow detachment is the key factor 2) the cavitation area is discontinuous, and the air cannot propagate from one separated blob to another. Future fast laser visualisation should help to clarify this last point.

As already mentioned, it is possible to correlate the nozzle flow features with the trend in penetration by actuating the upper valve and measuring the spray tip propagation. The penetration **Figure 11** confirms that the highly penetrating case is with low conicity. A convergent nozzle will enhance the shear generation and reduces the penetration. A largely divergent nozzle will enhance a stable cavitation presence and reduces also the penetration. The penetration reduction quantitative benefit will also depend from the other nozzle geometric parameter values that can be studied with the same experimental rapid-prototyping approach.

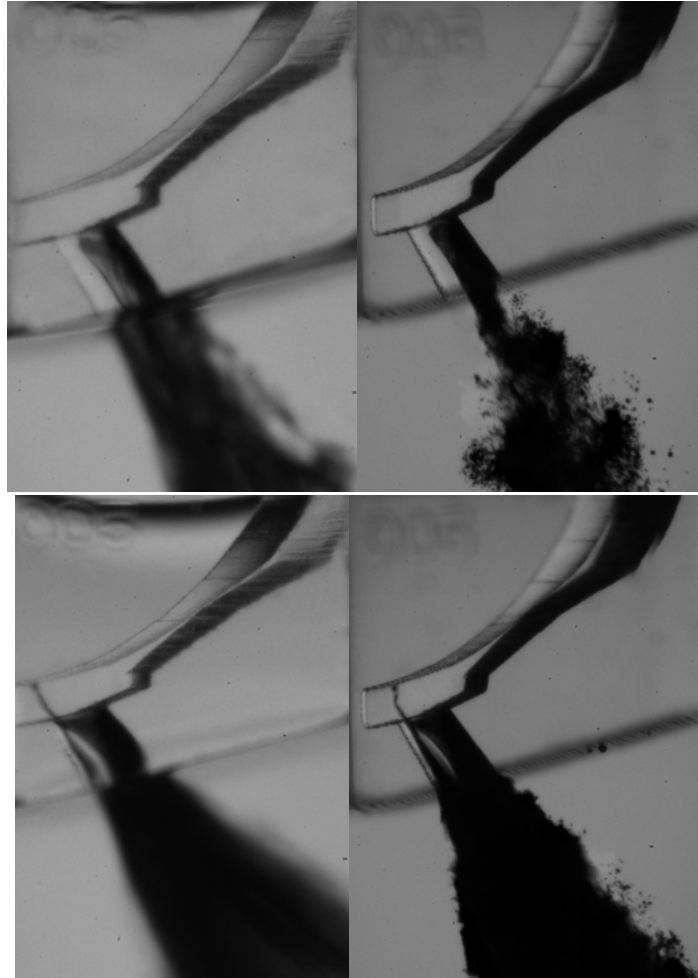


Figure 10. Instantaneous visualisations of in-nozzle cavitation, sample #5. Left: liquid in air; Right: liquid into liquid. Top: 10bar rail pressure. Bottom: 100bar upstream pressure. 1 bar downstream pressure condition.

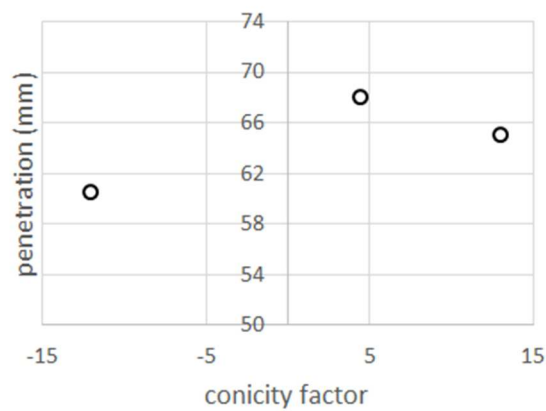


Figure 11. Penetration at 1.07ms after the hydraulic start of injection for the 3 variants at 100bar upstream pressure in 1 bar downstream condition.

Conclusions

Real-size transparent nozzles that can resist to engine operating fuel pressure were designed with the constraints to correspond to the real shape of the nozzle through an angular sector of the complete injector. The nozzles were produced using laser etched technique with fused silica. The edge radius and surface roughness are also found to be of the same order of magnitude compared to metal nozzle.

In the present paper the in-nozzle flow and the atomisation at the exit area have been characterised. Shear and string cavitation are identified. The first one is observed to be stable for this geometry. The second one is typically developing along the hole, often being attached to the roof. Its occurrence is high. The comparison of liquid-into-air condition to liquid-into-liquid condition indicates that the air presence is playing a minor role for the overall cavitation area for shear or string cavitation as visible when integrated during 2 microseconds.

Even if the upstream sac volume differs from a real nozzle, the penetration is used to return relative trends between nozzles. Highly converging or diverging nozzles reduce the penetration, that is coherent with the flow disturbance (turbulence and cavitation) observed inside the nozzle.

The present approach allows to generate realistic rapid prototyping of new nozzles that could be extended to multi-hole configurations. The technique allows to contribute to nozzle design by making design variation and parametrisation to better understand and control the role of the cavitation on the atomisation.

References

- [1] Soteriou C., Andrews R., Smith M., Direct injection diesel sprays and the effect of cavitation and hydraulic flip on atomization. SAE paper 950080, 1995.
- [2] Andriotis A., Gavaises, M., Influence of vortex flow and cavitation on near-nozzle diesel spray dispersion angle, *Atomization and Sprays*, 19(3):247–261, 2009
- [3] Blaine R. Parkin, Scale effects in cavitating flows, Hydrodynamics Laboratory California Institute of Technology Pasadena, California Report Wo. 21-8 July 31, 1952
- [4] Winklhofer, E., Kull, E., Kelz, E., Morozov, A. Comprehensive hydraulic and flow field documentation in model throttle experiments under cavitation conditions. Proceedings of the ILASS-Europe Conference, Zurich, 2-6 September, 2001
- [5] Mauger C., Méès L., Michard M., Lance M., Velocity measurements based on shadowgraph-like image correlations in a cavitating micro-channel flow, *International Journal of Multiphase Flow* 58, pp 301–312, 2014
- [6] Payri R., Salvador Rubio, F.J., Gimeno, J., O.H. Venegas Pereira, Study of cavitation phenomenon using different fuels in a transparent nozzle by hydraulic characterization and visualization. *Experimental Thermal and Fluid Science*. 44 pp235-244, 2013
- [7] H. Chaves, C. Ludwig, Characterization of cavitation in transparent nozzles depending on the nozzle geometry, 20th ILASS Europe, 2005
- [8] Sou A., Hosokawa S., Tomiyama A., Effects of cavitation in a nozzle on liquid jet atomization, *International Journal of Heat and Mass Transfer* 50 (17) pp 3575 – 3582, 2007
- [9] Mitroglou N., Lorenzi M., Santini M., Gavaises M., Application of X-ray micro-computed tomography on high-speed cavitating diesel fuel flows, *Exp. Fluids* pp 57:175, 2016
- [10] Arndt E.A. R., Cavitation in vortical flows, *Annu. Rev. Fluid Mech.* 2002. 34:143–75
- [11] Reid, B.A., et al., An investigation of string cavitation in a true-scale fuel injector flow geometry at high pressure. *Physics of Fluids*, 2010. 22(3): p. 1-3.
- [12] Jollet S., Hansen H., Bitner K., Niemeyer, D., Dinkelacker F., Experimental and numerical investigations of 90 μm real-size transparent nozzles with high pressure conditions, ILASS – Europe 2014, 26th Annual Conference on Liquid Atomization and Spray Systems, 8-10 Sep. 2014, Bremen, Germany
- [13] Nurick W. H., “Orifice cavitation and its effect on spray mixing”, *Journal of fluid engineering*, vol. 98, pp. 681-687, 1976.