Cavitation Inside High-Pressure Optically Transparent Fuel Injector Nozzles

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Abstract. Nozzle-orifice flow and cavitation have an important effect on primary breakup of sprays. For this reason, a number of studies in recent years have used injectors with optically transparent nozzles so that orifice flow cavitation can be examined directly. Many of these studies use injection pressures scaled down from realistic injection pressures used in modern fuel injectors, and so the geometry must be scaled up so that the Reynolds number can be matched with the industrial applications of interest. A relatively small number of studies have shown results at or near the injection pressures used in real systems. Unfortunately, neither the specifics of the design of the optical nozzle nor the design methodology used is explained in detail in these papers. Here, a methodology demonstrating how to prevent failure of a finished design made from commonly used optically transparent materials will be explained in detail, and a description of a new design for transparent nozzles which minimizes size and cost will be shown. The design methodology combines Finite Element Analysis with relevant materials science to evaluate the potential for failure of the finished assembly. Finally, test results imaging a cavitating flow at elevated pressures are presented.

1. Introduction

Elevated injection pressures and microscopic nozzle orifices are used in injection systems in modern direct-injection engines to enhance atomization and deliver sufficient fuel mass quickly. The flow inside the injector must turn abruptly to enter the nozzle orifice, which in many cases causes cavitation to appear on the downstream side of the orifice inlet corner. Cavitation is generally considered a hazard, because collapsing cavitation bubbles can damage the surfaces of durable metals such as hardened steels. In addition, while some forms of cavitation have been shown to be beneficial for atomization, even removing carbon deposits in gasoline injectors, hydraulic flip suppresses atomization completely[1]. Until cavitation is better understood and easier to control, it seems logical to design the injector nozzle in such a way as to prevent cavitation.

The most effective way to study nozzle orifice flow cavitation is to construct an injector with an optically accessible nozzle so that the orifice flow can be visualized directly. This is not a simple task. Optically transparent engineering materials are most often brittle at room temperature. While brittle materials often have higher elastic moduli and stronger theoretical strengths, flaws left from the processing required to create the desired geometry can significantly reduce the load capacity of the finished component.

An important issue with optical tips is to find a match between the indices of refraction for the nozzle material and the fluid used. If they are not matched, then the edges of the passage will appear dark in a shadowgram. That would make it difficult to image wall cavitation. Acrylic and quartz have an index that comes close to that of most fuels (and water) but unfortunately they have low tensile strength due to processing flaws. They usually break well below realistic fuel pressures. Sapphire, on the other hand, has thermal and strength properties similar to steel, but it is poorly index matched to the fluids of interest.

Optically accessible (OA) injector nozzles have been used in several past studies of interior flows of injector nozzle geometries found in direct-injection compression-ignition engines. Many of these past studies were performed at injection pressures significantly lower than those of the related industrial injector, due to the challenge of designing an OA injector which can withstand high injection pressures. To compensate, some used scaled-up geometries to match Reynolds number. Studies which attempted to reach realistic injection pressures will be summarized here, since these are the most relevant to the design presented in this paper, and ultimately are the most accurate when it comes to reproducing the flow of interest.

Arcoumanis et al. examined the effect of scaling geometries while matching Reynolds and Cavitation numbers in the real-size and scaled up geometry[2]. They found that the cavitation structures were different in the two geometries at similar cavitation numbers. Both geometry scales showed geometric cavitation on the downstream side of the upper orifice edge(with the injector pointing downward), and string cavitation existing on the opposite side of the orifice hole. The main difference observed by the authors was attributed to the difference in bubble residence time in the flow due to the different orifice lengths. The large scale injector was made of acrylic glass, while the real scale injector was made of a quartz rod attached to a Bosch common-rail injector body and surrounded by an acrylic support gallery. The acrylic piece was significantly larger than the injector's original steel nozzle. Reid et al. used sapphire to create a simplified version of the geometry found in valve-covered-orifice (VCO) injectors[3]. They achieved injection pressures of 2000 bar with the design. It seems that the orifice was constructed by layering sapphire plates in the axial direction with a series of thru holes which formed the final geometry. This was a clever way to simplify the processing of the parts. How the device was sealed, and how the plates were held in place, was not included in the published results. Two forms of string cavitation were observed: one which formed in the vortices attached to the part of the geometry designed to mimic the needle, and another which formed in a vortex that connected two orifice holes.

Badock et al. achieved elevated injection pressures using acrylic nozzles, although much like Arcoumanis et al, the piece was significantly larger than the original injector nozzle[4]. Studying primary breakup of a spray in such a nozzle is impossible due to the lensing effect of the surface of the drilled reliefs which fix the length of the nozzle orifice passages. Blessing et al. achieved injection pressures of 800 bar using an acrylic injector nozzle with a single off-axis orifice[5]. The design was compact enough to allow the primary breakup of the spray emitting from the nozzle orifice to be studied simultaneously with the in-nozzle orifice cavitation. Unfortunately, no further information regarding the design, such as dimensions or sealing mechanism, was provided. Another effort which deserves mention is the recent study by Butcher et al[6]. The group constructed a quartz nozzle in order to study flash boiling sprays relevant to spark-ignition engines and even installed a modified needle to reduce the stress concentration in the nozzle from the force of the needle seating. Their injection pressures were limited to 40 bar.

The most recent study that achieved elevated injection pressures is that of Mitroglou et al[7]. The authors examined the cavitation structures inside an optically transparent VCO geometry with six orifice holes. They reached 400 bar, but due to slow flaw growth and the desire to collect enough data to build ensemble averaged images of cavitation structures, the injection pressure was limited to 300 bar. Cavitation was observed on both sides of the orifice, as in the earlier study of Arcoumanis. In this study, string cavitation was observed only during the opening phase of the needle valve, and corresponded to the location of a vortex attached to the injector needle face.

To sum up, the three most common materials used in OA injector nozzle designs are acrylic glass, sapphire, and quartz/fused silica. There are more studies which successfully reach elevated pressures with acrylic than the other materials. In most of these studies, a large piece was used and that made it difficult, if not impossible, to simultaneously visualize the spray formation region and the orifice flow. This was necessary to reach elevated injection pressures with these designs.

2. Injector Design

The real injector has orifices approx. 0.75 mm in diameter, which have a large angle of separation between their central axes and the central axis of the injector. The engine belonging to the real injector is a two-stroke marine diesel engine, with a large exhaust valve occupying the center of the cylinder. This causes the injectors to be mounted in the periphery of the cylinder head, and as a result, the sprays are aimed inwards toward the middle of the cylinder. The orifices in the real injector are grouped in a line and oriented so that the sprays create a fan-like pattern. Unlike most road vehicle Diesel engine fuel injectors, these injectors use a hollow stop shaft to control injection, which has radial holes that allow the fuel to through its hollow center and enter the sac volume.

The transparent injector used in this study was half-scale. The injector had only two orifices to simplify observation of primary breakup of the isolated sprays and to allow for observation of potential cavitation between the two orifices. During the design process a commercial Finite Element Analysis (FEA) tool was used to estimate the stresses in the finished design. The nozzle has a symmetry plane that passes through the central axes of the two orifice holes, and this was used to reduce the computational domain in the FEA's. For the analysis, the injection pressure of the real device (800 bar) was applied as a boundary condition to the interior surfaces of the acrylic nozzle piece. Given that brittle materials most often fail in tension, sapphire clamps were added to the design to compress the nozzle from the outside and minimize the tensile forces at the inner surfaces. Since the clamps were on the outside of the nozzle, an optically transparent material had to be used for their construction. Sapphire was chosen due to its high durability. In a sense, this made the sapphire clamps the load bearing components of the nozzle, even though the piece to which the pressure was applied directly was made of acrylic.

The final design with 3 sapphire clamps, fabricated and assembled, is shown in Figure 1. The outer dimensions of the nozzle are 21.5 mm in the viewing direction in Figure 1 and 6.75mm in the vertical direction. O-ring seals are used on either side of the nozzle.

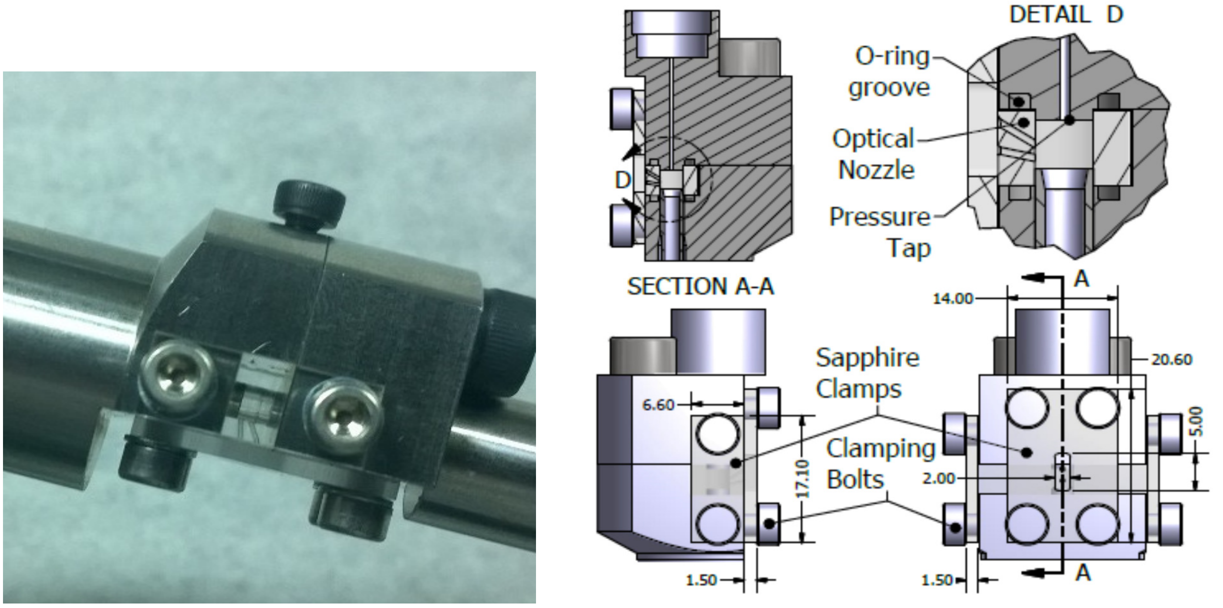

Figure 1: Design for high-pressure optically accessible injector nozzle with 3 sapphire clamps.

3. Results and Discussion

This design was tested with diesel fuel supplied by a commercial reciprocating piston pump with 3 stages, driven by a large electric motor. The original injection duration was set to 250ms, but the sac volume pressure measurements indicated that the pump was not able to sustain the commanded pressure for the entire period. The resulting injection period was approximately 100ms, and the injection pressure tapered off slowly during this period.

Figure 2: Representative still shot of the flow during steady state in the optically accessible nozzle when the injection pressure is at 350 bar.

The flow inside the nozzle was captured in a transillumination configuration with a Phantom V1210 high-speed camera. Because the ambient was at atmospheric back pressure, the orifice flow cavitated easily. A representative image with an injection pressure of 350 bar is shown in Figure 2. A full video of the interior flow as well as of the orifice flow and spray formation region at this flow condition has also been provided. This flow condition is at a Reynolds number of approximately 85,000. During the entire injection period, wall cavities appear on the side of the orifices furthest away from the injector body, where the inlet corner is sharper. The cavities extend almost all the way to the orifice exits, where they shed clouds that perhaps survive outside the injector body. No evidence of string cavitation in the sac volume can be seen, although vorticity is evident in the high-speed videos. Even without string cavitation, transient cavitation cloud shedding appears on the side of the orifice opposite the standing wall cavity in the orifice with the larger inclination angle from the central axis of the injector. The standing wall cavity in this orifice exists along the entire orifice inlet edge, so perhaps these clouds are shed from the wall cavity, in which case they would be a result of geometric cavitation. An important difference between this injector and other injectors in past studies is the absence of a needle. The stationary stop shaft is hollow, and so the largest vortex in the sac volume actually exists at the farthest axial position in the sac volume, where the flow turns back upstream to enter the nozzle orifices. String cavitation between the orifices was not observed in these studies.

When the nozzle failed, the sac volume pressure would drop suddenly, and this was seen in the sac volume pressure measurement. The ultimate pressure that the final design could withstand was 600 bar. While this injection pressure isn't as high as some past studies, the nozzle orifices of this design are unusually large.

4. Conclusions

An optically transparent fuel injector nozzle was designed using an approach which evaluated more carefully the nozzle's propensity for failure due to the materials used in its construction. This approach considered the most common failure mechanisms for brittle materials, and used Finite Element Analysis to resolve the operating loads on the nozzle in detail. The design used sapphire clamps with simple geometries to compress an acrylic nozzle piece in order to minimize the tensile stresses on the inner surfaces of the piece where the pressure from the fuel was applied. For a given pressure capacity, this design is less expensive than one constructed exclusively from sapphire and more durable than one constructed exclusively from acrylic.

The cavitation in the orifices showed dependence on geometry, specifically on the inclination angle of the central axis of the orifice. While cavitation was found on both side of the orifice with the larger inclination angle, it was not due to string cavitation, which is what cavitation in this area has been most commonly attributed to in past studies.

Future work will remove the clearance holes from the sapphire clamps, and instead use simpler sapphire pieces mounted inside stainless steel clamps. This change is expected to reduce the stress concentration in the sapphire pieces and allow greater clamping forces than were possible with the previous design. The new pieces will be tested to confirm their performance and then experiments will be conducted over a range of back pressures (cavitation umbers) in a pressurized chamber. This will produce a range of cavitating flows for further study.

Acknowledgements

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