*ICLASS 2009, 11th Triennial International Annual Conference on Liquid Atomization and Spray Systems, Vail, Colorado USA, July 2009*

# The Performance of a Pressure Atomizer with Upstream Flow Obstructions

P. A. Corber*[1] and S. Tavoularis[2]
[1]Gas Turbine Laboratory, Institute for Aerospace Research
National Research Council of Canada
Ottawa, ON K1A 0R6, Canada
[2]Department of Mechanical Engineering
University of Ottawa
Ottawa, ON K1N 6N5, Canada

**Abstract**

The internal flow and the spray of a kerosene simulant formed by a pressure atomizer with an orifice diameter of 1 mm and a length to diameter ratio of 10 were studied at injection pressures between 70 and 5000 kPa. Obstructions to flow were introduced inside the injector to examine their effect on the injector's performance. Visualization of the flow inside the injector indicated that the obstructions caused the flow to cavitate. However, even without any obstruction, cavitation was observed at injection pressures as low as 200 kPa. Four distinct modes of cavitation have been identified, depending on the mass flow rate of fluid through the nozzle and the type of obstruction. Images of the resulting spray indicated that cavitation enhances atomization significantly. The distributions of droplet sizes and velocities in the spray were measured 100 mm downstream of the nozzle face using single-component phase Doppler particle analysis. For a fixed fluid flow rate, the droplet size distribution was found not to be affected by changes in the cavitation pattern.

## Introduction

The occurrence of cavitation in the interior of atomizer nozzles has been shown to greatly affect atomization [1] [2] [3]. Several theories have been proposed to explain this phenomenon, although the exact process by which this occurs is not completely understood [4]. It has been argued that cavitation improves atomization simply because vapour occupies some of the flow cross section inside the nozzle, which results in an increase in the liquid's exit velocity thus generating greater shearing forces between the injected liquid and surrounding air [3]. The generation of strong disturbances by collapsing vapour bubbles in the nozzle passage has also been used to explain the enhancement of atomization by cavitation [1]. Another hypothesis speculates that a high gas volume fraction in the nozzle enhances atomization by increasing surface imperfections which facilitates the release of droplets, by increasing compressibility which strengthens wave growth in the jet, and by decreasing the viscosity in two-phase flow regions [4]. The objective of the present work is to examine experimentally the dependence of the spray properties upon the geometry of obstructions introduced in the nozzle and, in particular, to identify any possible relationships between atomization and the patterns of cavitation caused by the different obstructions.

## Materials and Methods

All tests were performed at the National Research Council of Canada, Gas Turbine Laboratory's Spray Dynamics Laboratory (SDL), which is equipped with circuits designed to deliver liquid fuel to spray nozzles. The experimental operation was controlled and monitored by a data acquisition system. The liquid fuel was drawn from a reservoir and supplied under pressure to the spray nozzle through a line using a variable speed drive pump. Flow control was achieved by tuning the pump and by pneumatic control valves, which allowed the operator to adjust the fuel delivery by pressure or flow rate. The fluid flow rate was measured by a Coriolis flow meter and the temperature was measured by a standard K-type thermocouple. The fuel delivery pressures were measured at the nozzle using pressure transducers. The liquid used for all reported results was MIL-PRF 7024C Type II, which has physical properties similar to kerosene but is less volatile, thus being safer to use in a laboratory setting. The experimental setup also included a three-dimensional linear motion system, which moved the injector assembly rather than the optics, to minimize errors due to possible misalignments of the optical components. The uncertainty of the motion controllers and encoders for the placement of the instrumentation was calculated to be 0.075 mm.

*Corresponding author

The injector used in this study is shown in Figure 1 and would be classified as a pressure atomizer. The geometry of the nozzle was selected in order to match those that have been employed successfully in previous research programs with similar motivations [4]. It has the advantages of a simple geometry that is easy and inexpensive to manufacture and an orifice size that is large enough to permit visualization of the internal flow but also small enough to produce a spray at moderate injection pressures. The injector was made from acrylic material (Plexiglas) with plane surfaces machined on the sides to eliminate refraction of light at the interface between air and nozzle material.

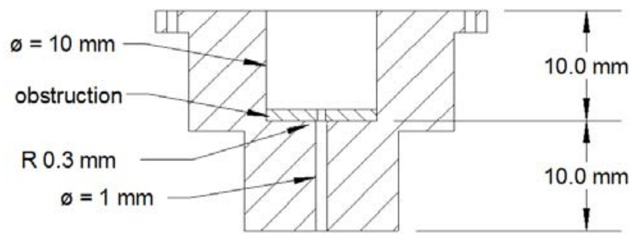


**Figure 1.** Nozzle geometry.

In order to induce various patterns of cavitation, the injector was equipped with the various obstructions shown in Figure 2. All of the obstructions were made of steel and fitted inside the injector directly upstream of the 1 mm diameter capillary. The injector is referred to as “open” or “unobstructed” when no obstruction was present.

| Screen | Circular Orifice | Slot | Meniscus | Bar |
|---|---|---|---|---|
| Wire mesh with 1.57 wires per mm and wire diameter 0.24 mm | 0.80 mm diameter hole | 0.50 mm slot spanning the orifice | Semi-circular opening that blocks approximately half of the orifice | Two semi-circular openings with a 0.5 mm thick bar spanning the orifice |

**Figure 2.** Nozzle obstructions.

Flow visualization of the spray and of the internal nozzle flows was performed using high-speed video and digital photography. For both methods, a high-output flood light was used to back-light the flows inside and outside of the nozzle. This method produced good quality images for the spray as a whole and of the cavitation occurring inside the injector. The break-down process of the liquid jet was visualized by using sufficiently short exposures. The high speed video of the flows inside the injector permitted observation of unsteady internal flow patterns. A Nikon D70s single-lens reflex (SLR) camera equipped with a 24-70 mm 3.5-5.6/f autofocus lens was used to photograph the spray. A Canadian Photonics Lab Inc. Mega Speed digital video camera, equipped with a Tamron 180 mm f/3.5 macro autofocus lens was used to film the internal nozzle flows. This video camera was set to capture images at 6000 frames per second with exposure times of 75 µs.

A Phase Doppler Particle Analyzer (PDPA; TSI Inc.) was used to measure the droplet size and the axial velocity component in the spray. The PDPA optics were set up in a 30$^o$ forward scatter configuration. A 500 mm focal length transmitter was used in conjunction with a 150 µm receiver slit to reduce the size of the measurement volume. PDPA measurements were made on axial planes that were 50, 100, and 150 mm downstream from the nozzle face. Only data collected on the 100 mm plane are presented in the following.

**Results and Discussion**

Representative flow visualization results are presented in Figures 3 to 7. The upper rows of images show the internal nozzle flow whereas the lower rows show the resulting spray. The leftmost column shows a low pressure condition, which is free of cavitation. The second column shows images at the lowest mass flow rate and injection pressure at which cavitation was observed. Because the working fluid is transparent, its internal flow patterns are invisible. The dark regions observed inside the injector are believed to be vapour pockets or bubbly regions due to cavitation. Results with the "meniscus" and "bar" obstruction have not been included for lack of space, but they are quite similar to the results obtained with the "slot" injector.

The results for the unobstructed injector are shown in Figure 3. The 70 kPa flow condition is a non-cavitating case (the grey marks in the image are scratches on the Plexiglas caused by machining). At this condition, the liquid exits the nozzle as a column. At an injection pressure of approximately 200 kPa, the flow begins to cavitated, which coincides with the first signs of liquid column break up. The internal flow conforms to the conventional pattern of cavitation inception within the injector [5], namely that vapour is released just downstream of the inlet to the capillary, as a result of the pressure drop in the separation bubble around the sharp corner. The 19 g/s flow condition is very unstable and the image shown in the second column cannot capture the temporal variation of the flow. When the flow rate is increased, however, the instabilities subside. In columns 3 – 5 of Figure 3, some gas can be observed escaping the recirculation zone, in the form of small bubbles convected down the capillary and leaving dark streaks in the image. At the maximum flow rate tested, the bulk fluid velocity was approximately 73 m/s. At this speed, a bubble would travel the length of the capillary in 137 ms, so that it could be photographed only once before it exited the injector. Furthermore, each bubble would travel an average distance of 5.4 mm during the exposure time, and thus its image would appear as a streak rather than an approximate sphere. This explains the streaky appearance of cavitating flows inside the injector. Even at the lower flow rates presented, the maximum acquisition rate of the video camera was not high enough to freeze the motion of the cavities.

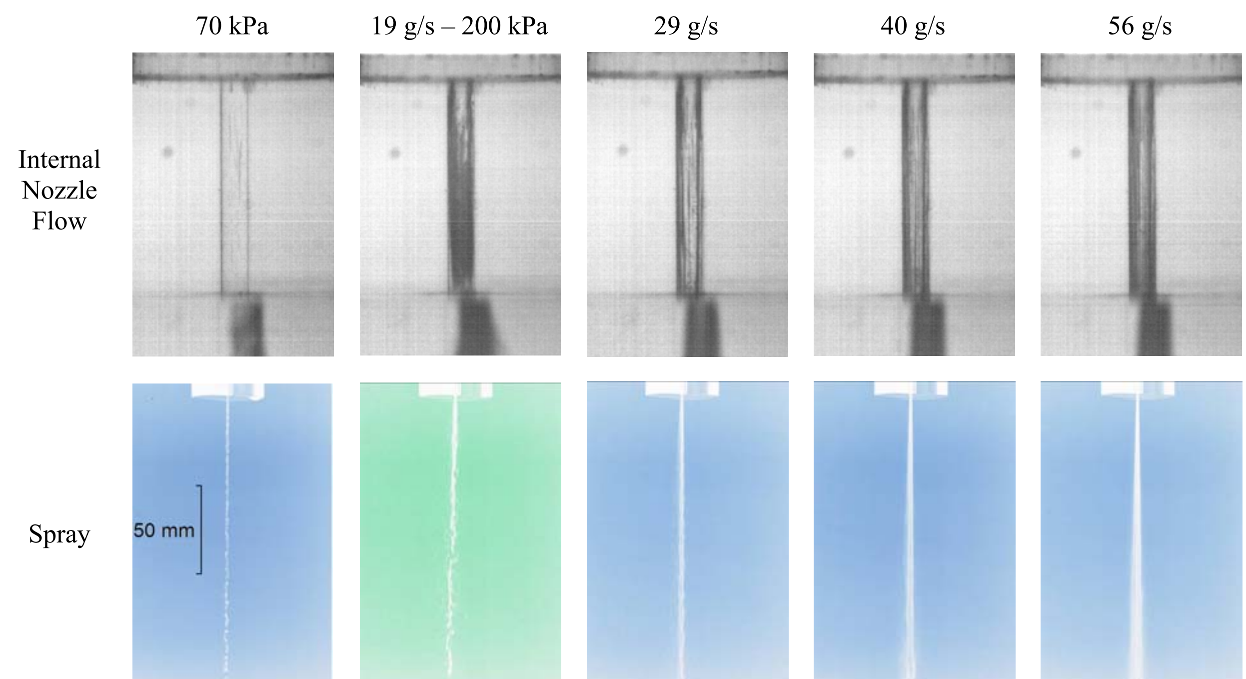


**Figure 3.** Flow visualization of the unobstructed injector.

The flow results for the "screen" obstruction are presented in Figure 4. The cavitation inception occurs at an injection pressure of 200 kPa, comparable to that for the unobstructed injector, but at a flow rate that is lower than that in the unobstructed injector, due to the pressure loss across the screen. In this case, cavities form in the low-pressure wakes of individual wires. A large concentration of cavitation bubbles can be seen just downstream of the obstruction, with a few bubbles propagating down the capillary. Again, the inception of cavitation is observed to coincide with the liquid jet break-up. Increasing the flow rate to 19 g/s (Column 3 of Figure 4) fills the nozzle with vapour, saturating the camera. Unfortunately, there is very little information that can be extracted regarding the internal flow at this condition. Further increase in the flow rate did not result in any observable change inside the nozzle, although it improved atomization and widened the spray cone angle. The results for the slot obstruction, shown in Figure 6, are similar to the previous case.

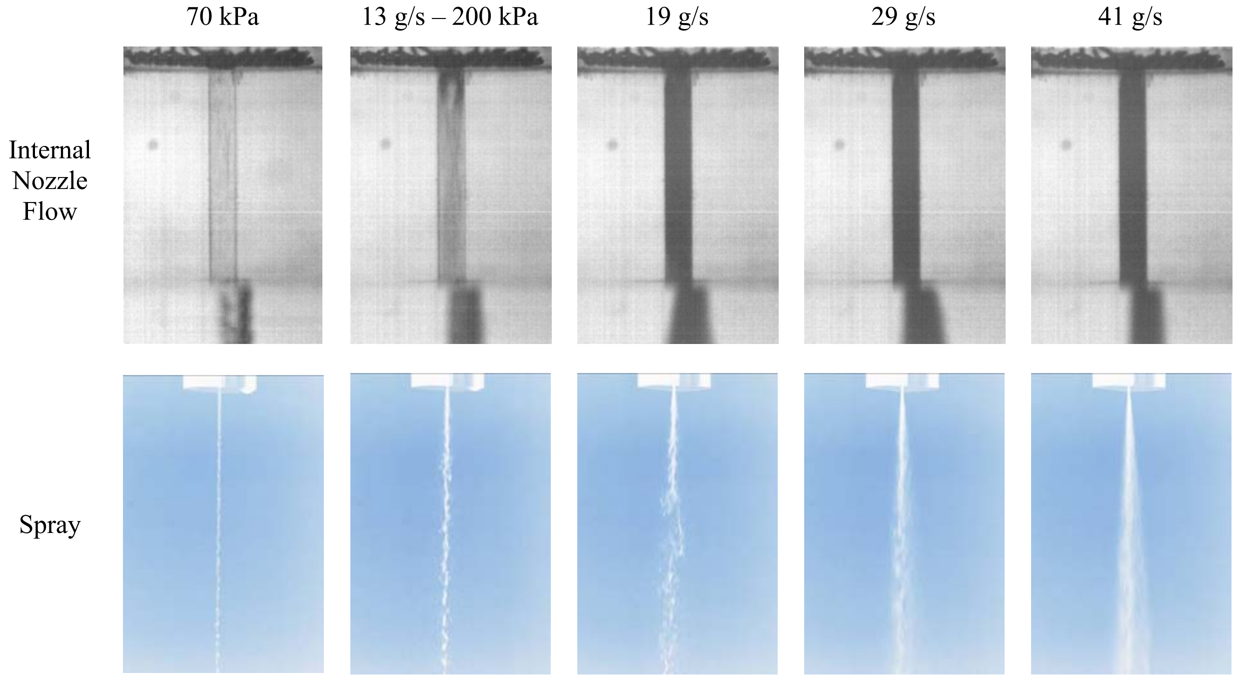


**Figure 4.** Flow visualization of injector with the “screen” obstruction.

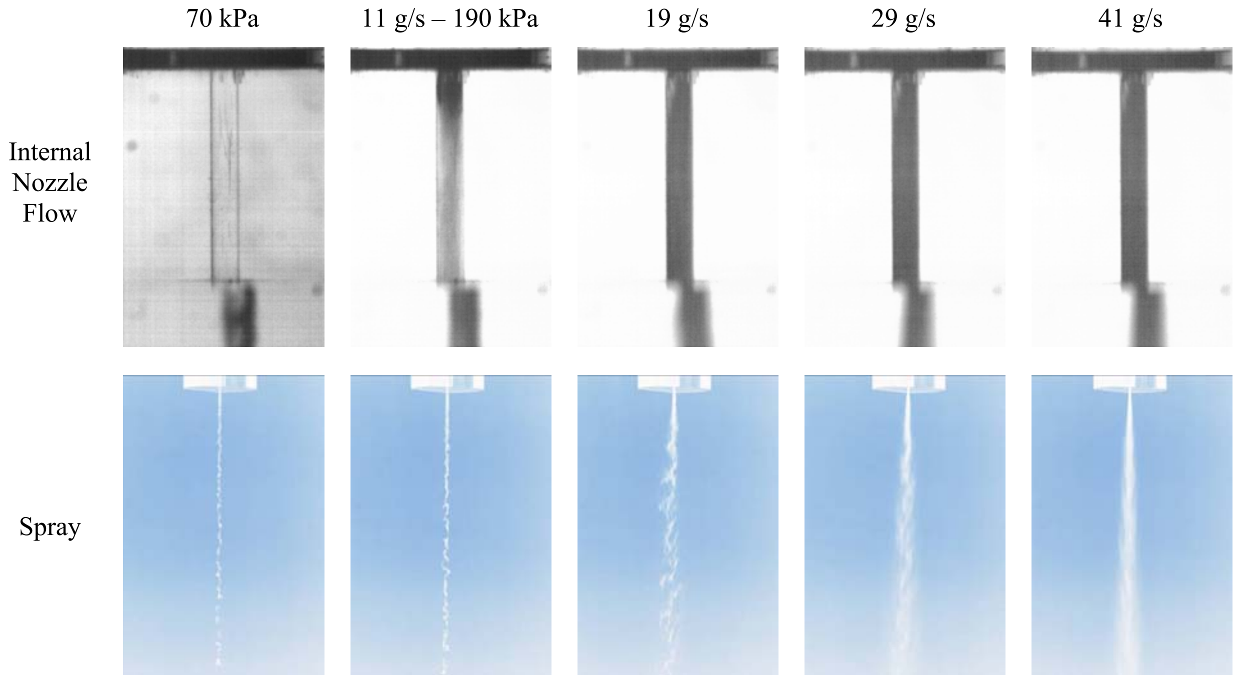


**Figure 5.** Flow visualization of injector with the “slot” obstruction.

The "circular orifice" obstruction changes the performance of the injector significantly. These results are shown in Figure 6. At a flow rate of 11 g/s, the flow was cavitating and the vapour bubbles filled the capillary. The change of the jet appearance is dramatic, with the liquid beginning to break up approximately 30 mm from the nozzle face. A further increase in flow rate results in another change in the internal and external flow structures. At 19 g/s, the internal flow appears to have separated from the capillary wall and does not reattach. The result is a suppression of the atomization, with a smooth liquid column emerging from the injector, indicating the occurrence of hydraulic flip. It is interesting to note that, for all the injector configurations tested, the onset of cavitation occured at approximately the same pressure and not at a particular mass flow rate. In addition, the cavitation pattern did not seem to correlate with the flow rate. A comparison of Figures 5 and 6 shows that the internal flows were drastically different, despite having comparable flow rates and injection pressures. The flow visualization results give evidence of four distinct cavitation modes, which are described in Figure 7.

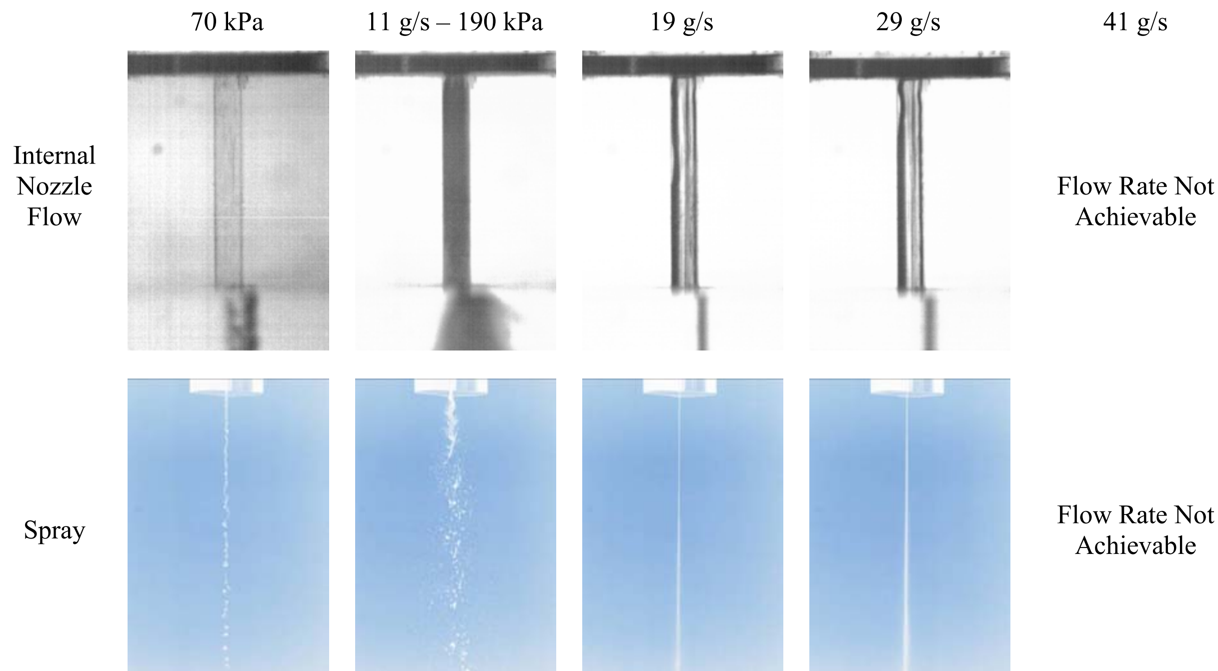


**Figure 6.** Flow visualization of injector with the "circular orifice" obstruction.

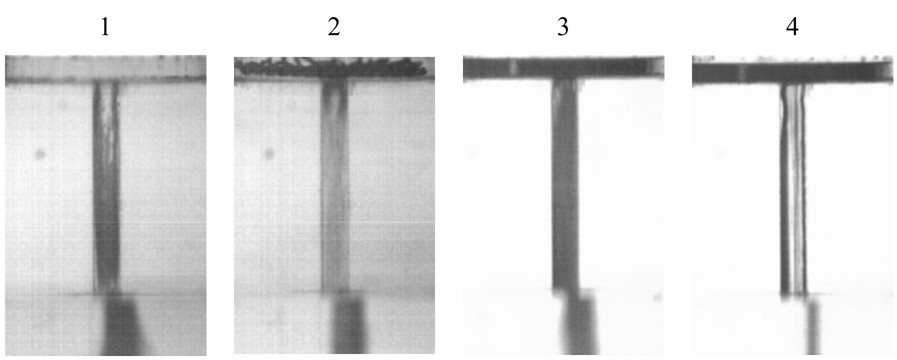


**Figure 7.** Flow visualization of the four distinct cavitation structures: 1. Cavitation at the entrance to the capillary, highly unsteady with a large amount of vapour (unobstructed injector); 2. Cavitation caused by the "screen" obstruction, with cavitation bubbles convected downstream; 3. Cavitation bubbles filling the capillary; 4. Hydraulic flip.

Figure 8 shows PDPA measurements of the droplet axial velocity and size for the “screen” and the unobstructed injectors. Measurements at two mass flow rates are presented, which correspond to cavitation structures 1, 2, and 3, as shown in Figure 8. For the same mass flow rate, the maximum droplet velocities produced by the two injectors were comparable, as expected. The measurements also confirm the visual observations that “screen” obstructed injector produced a wider spray than the unobstructed one. The screen not only changes the structure of the cavitation but will also likely increase the turbulence in the flow. This is in agreement with previous research indicating that increased turbulence results in a spray with a wider cone angle [4].

Despite the large differences in the internal flow structures and spray cone angles, the sizes of droplets produced by the two injectors were comparable. One explanation for this could be the occurrence of secondary droplet break-up. Because the measurements were made far downstream from the nozzle exit, large droplets forming near the nozzle exit could have broken into smaller ones by the time they reached the measuring position. An unexpected result is that larger droplets were found at the centre of the spray, where the velocity is at a maximum. This could be at least partially attributed to higher measurement bias near the centre of the spray, where the laser beams have to penetrate a large amount of fluid to reach the measurement volume, and the light scattered by the droplets has to travel through a large amount of fluid to reach the detector; so, it is possible that light scattered from the smaller particles could be further attenuated and scattered by other particles, thus biasing upwards the average measured droplet diameter. The apparent presence of larger droplets near the axis of the jet could also be interpreted as an indication that the spray had a non-atomized, liquid core.

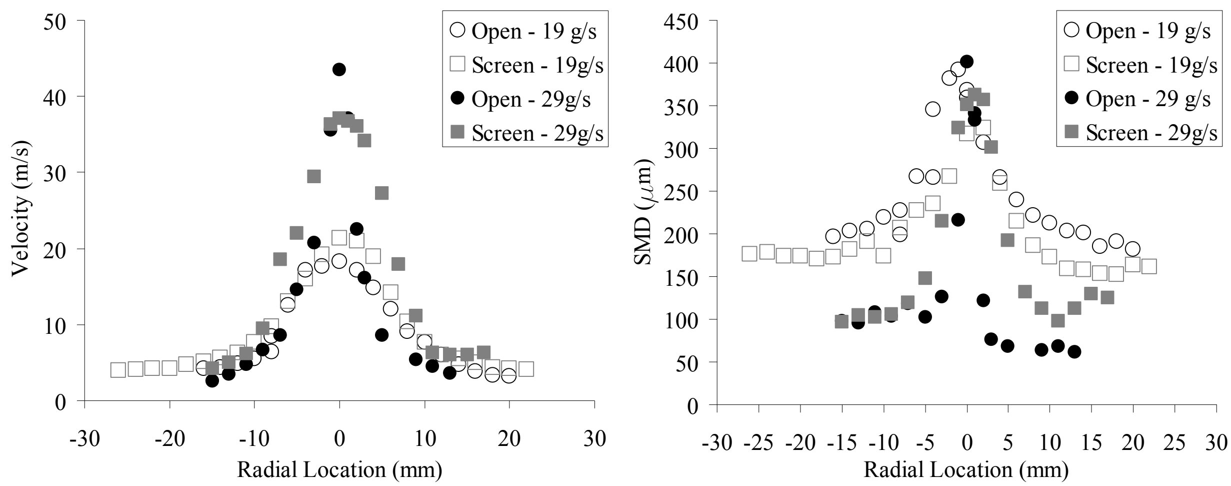


**Figure 8.** Transverse variations of the droplet axial velocity (left) and the Sauter-mean droplet diameter (right), measured with PDPA at 100 mm from the injector face.

The results indicate that obstructions inserted in the injector have significant effects on the internal nozzle flow. Although these obstructions also introduce pressure drop, thus requiring an increase in the injection pressure to achieve the same flow rate as that in the unobstructed nozzle, they generally improve atomization and increase the cone angle of the spray. For a fixed flow rate, the size of the droplets in the far field seems to be unaffected by obstructions.

**References**

1. Hiroyasu, H., *Atomization and Sprays* 10:511-527 (2000).
2. Tamaki, N., Shimizu, M., and Hiroyasu, H., *Atomization and Sprays* 11:125-137 (2001).
3. Dumont, N., Simonin, O., and Habchi, C., *Eighth International Conference on Liquid Atomization and Spray Systems*, Pasadena, CA, USA, July 2000, pp. 314-323.
4. Stahl, M., Damaschke, N., and Tropea, C., *Tenth International Conference on Liquid Atomization and Spray Systems*, Kyoto, Japan, August 2006, A1-05-116.
5. Ruiz, F., *Fifth International Conference on Liquid Atomization and Spray Systems*, Gaithersburg, MD, USA, July 1991, pp. 595-602.