Flow Visualization of a Pressure Swirl Nozzle Before Full Atomization Stage

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Figure 1, Depiction of the Flow Phenomenon exiting a Pressure Swirl Nozzle at a Lower Pressure/Volumetric Flow than the Full Atomization Stage

Introduction

The image above in Figure 1, was taken for the first Image/Visual project in the MCEN 5151, Flow Visualization course at the University of Colorado, Boulder in the Fall 2022 semester. The purpose of Flow Visualization is to capture and observe fluid phenomena while exploring the interface between art and science [1]. The image in Figure 1 depicts the phenomenon caused by a Pressure Swirl Nozzle (PSN) when used below maximum pressure known as a "Tulip" according to Lachin [2]. PSNs are used in water atomization, a process that minimizes size of water droplets to a size of about 100 microns [3], about the width of a human hair. These miniscule droplets are often used in the commercial production of metal powders [3]. The nozzle used for this process, a PSN, is very commonly used for creating a "mist" effect and can be found in any garden hose that has a "Mist" mode on the nozzle. Using a common garden hose with a mist nozzle, the Pressure Swirl Nozzle phenomenon was able to be photographed. This experiment was conducted outdoors in front of a dark wooden fence, as depicted in the background of Figure 1.

Fluid Physics

The flow apparatus used in this experiment is a Pressure Swirl Nozzle (PSN) connected to a hose. A cross-section sketch of the PSN is shown below in Figure 2.

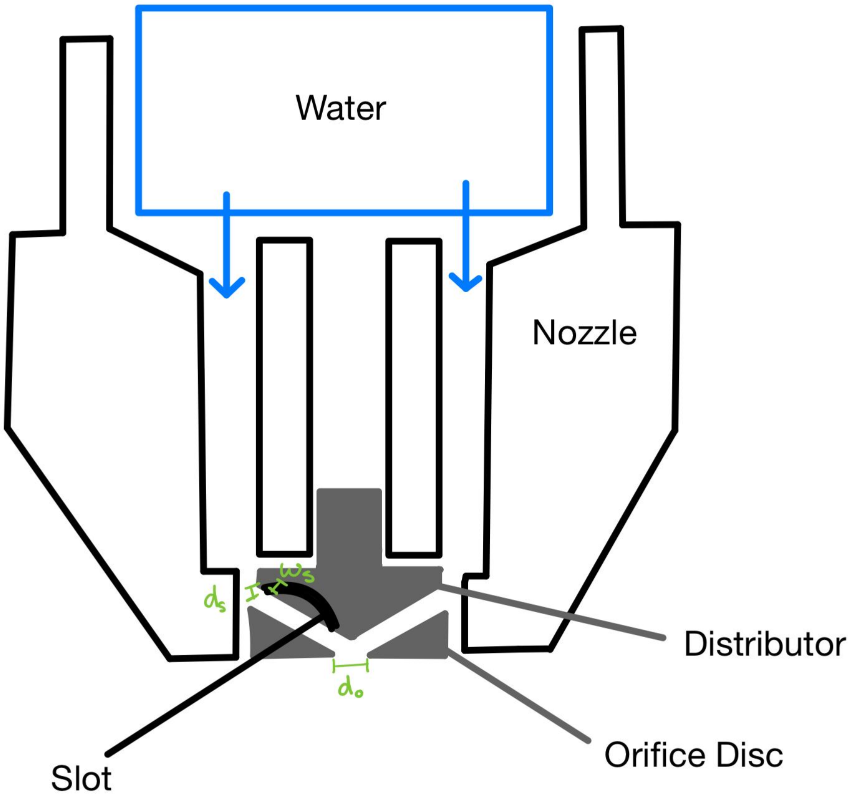

Figure 2, Cross Section Sketch of Pressure Swirl Nozzle Used in the Experiment. This sketch is based off of Figure 1 of Lachin (2020) Reference [2].

The variables included in Figure 2 are as described below:

$$d_o = \ Orifice\ Outlet\ Diameter\ [2]$$

$$d_s = \ Distributor\ Slot\ Depth\ [2]$$

$$w_s = \ Distributor\ Slot\ Width\ [2]$$

The outlet diameter of the hose used in this experiment was about 0.025 inches or roughly 0.635 millimeters, found through measurement. Due to how close it was to one of the outlet diameters of a nozzle used in the experiment by Lachin [2], for calculation purposes the dimensions of Nozzle 2a were used to calculate the following Reynolds Number and Euler Number. The dimensions and calculations are below, refer to Lachin [2] Section 3 for more details in Dimensional Analysis:

$w_s = 0.239\ mm$ Slot Width for Nozzle 2a [2]

$d_s = 0.387\ mm$ Slot Depth for Nozzle 2a [2]

$n_s = 4$ Number of Slots for Nozzle 2a [2]

$d_h = \frac{2 \cdot w_s \cdot d_s}{w_s + d_s} = 0.295 \times 10^{-3} m$ Slot Hydrodynamic Diameter for Nozzle 2a [2]

$A_s = n_s \cdot w_s \cdot d_s = 0.370 \times 10^{-6} m^2$ Total Section of Slots for Nozzle 2a [2]

$\rho = 1000\ kg/m^3$ Density of Water [2]

$\mu = 1 \times 10^{-3} Pa \cdot s$ Dynamic Viscosity of Water [2]

$V = 0.1\%(1.073 \times 10^{-3})\ m^3/s$ Volumetric Flow Rate of a Garden Hose (At 0.1% Power)

$$Re = \frac{\rho \cdot V \cdot d_h}{\mu \cdot A_s}$$ Reynolds Number for Pressure Swirl Nozzle Flow [2]

$$Eu = 29.97 \cdot (Re^{.2})$$ Euler Number for Pressure Swirl Nozzle Flow from Experiment [2]

$$Eu^* = \frac{Eu}{Eu_{Atomization}} = \frac{Eu}{120.54}$$ Normalized Euler Number for Atomization from Experiment [2]

$$Re = \frac{(1000kg/m^3)(.001 \cdot 1.073\times10^{-3}m^3/s)(.295\times10^{-3}m)}{(1\times10^{-3}Pa \cdot s)(.370\times10^{-6}m^2)} = 860$$

$$Eu^* = \frac{116}{120.54} = 0.96$$

The Normalized Euler number shows that the flow in this experiment depicted in Figure 1, is nearly at full atomization but not quite (about 96% full atomization). This gives insight to why the shape is formed. In a Pressure Swirl Nozzle the slots in the distributor manipulate the water molecules causing centrifugal force. The centrifugal force is what causes a hollow cone to exit from the nozzle, however at Reynolds numbers under 1000, there are frictional forces within the fluid present that restrict flow and prevent full atomization. This results in a semi-formed cone that looks like a “bubble” as seen in Figure 1. Below in Figure 3, other flow pictures have been taken by Lachin [2] that depict the flows at different Reynolds numbers/flow rates. As the Reynold’s number increases so does the air core diameter [2] until at full atomization the air core is at a maximum. In Figure 1, the air core is at a perfect balance just before full atomization causing a closed “Bubble” effect from the PSN instead of the half “Tulip” depicted in Figure 3 [2].

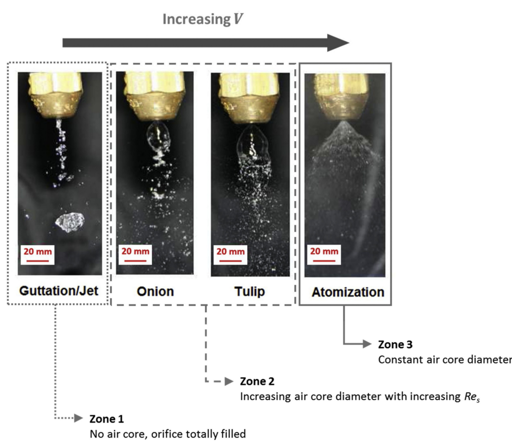

Figure 3, Figure 6 from Lachin [2] “Spraying regimes observed when increasing the liquid flow rate (nozzle 4d, water at T = 20 Celsius).”

Visualization Technique

The visualization techniques used in this experiment to take the photograph in Figure 1 were quite simple and raw. This photo was taken outdoors with a garden hose that can be found at any house. The hose was secured in place but no tripod was used, however a tripod would be highly recommended for repeating this experiment. There were no particles added to the water and a dark wood fence background was used, but a solid black background would be better for repetition. The time of day this was taken was about an hour before sunset so there was plenty of light but no direct sunlight. Two phone flashlights were used: one facing directly upwards illuminating the bottom of the bubble and another right above the camera at an angle of about 30 degrees above the camera view.

Photographic Technique

The image was taken with many different photographic techniques that complimented the experiment well. The distance from object to lens was about 3 inches with a field of view of about 45 degrees. The lens used was a Canon zoom lens with a 18-55mm focal length, 1:3.5-5.6 aperture and a thread diameter of 58mm. The digital camera used with this lens was a Canon EOS Rebel T1i. For the image taken in Figure 1, the aperture was f/8.0, the exposure is 1/100, a focal length of 53mm, and a 3200 ISO. The original image had a pixel size of 4752px width by 3168px height. This was then cropped down to 4511px width by 1776px height to allow the main subject to fill the entire frame. Other post-processing of the image included: increasing the shadows, decreasing the highlights, adjusting the base curve into an S-curve, slightly increasing the exposure, increasing sharpness, and adjusting the orientation of the photo for a level flow. The original, raw image is included below in Figure 4. The purpose of the post-processing was to enhance the image of the bubble and adjust the white balance and contrast. There was less of a focus on color as the water is transparent and the brown background was simply used to contrast the clear fluid.

Figure 4, Raw/Original Image from Figure 1 of a Pressure Swirl Nozzle at a stage before full atomization

Image Conclusions

The image taken in this experiment in Figure 1 captured a unique but common phenomenon in a way that is nearly simple. Using common items such as a garden hose and a real background of a fence instead of an all black gives it an aspect of realism. It is something that catches the fascination of any viewer and gives a curiosity of wanting to repeat this experiment or grab a hose and see it for themselves. A better experiment set up with a cleaner hose, tripod, and LED light stands would greatly improve the quality of this image. In the future, an experiment that is able to track the exact hose pressure or volumetric flow rate along with the length of the bubble would greatly benefit the analysis and prediction of this intriguing phenomenon. From an artistic standpoint, a great improvement to this experiment would be dyes in the water with different lighting, such as UV dye and blacklight, or any particle tracing that would show how the water is twisting in this flow and forming a bubble before scattering into the world. This experiment showed the curiosity and beauty in a common aspect of any person’s life, hopefully it will open a viewer's eyes to look for more beauty in fluid everyday.

References

[1] Hertzberg, Jean. “SYLLABUS MCEN 4151/5151/ FILM 4200/ ARTF 5200/ ATLS 4151/5151 Flow Visualization: The Physics and Art of Fluid Flow Fall 2022.” *FLOW VISUALIZATION A Course in the Physics and Art of Fluid Flow*, 18 Aug. 2022, https://www.flowvis.org/wp-content/uploads/2022/08/syllabusF22.pdf.

[2] Lachin, K., et al. “Dimensional Analysis Modeling of Spraying Operation – Impact of Fluid Properties and Pressure Nozzle Geometric Parameters on the Pressure-Flow Rate Relationship.” *Chemical Engineering Research and Design*, Elsevier, 12 Aug. 2020, https://www.sciencedirect.com/science/article/pii/S0263876220303518#fig0015.

[3] Lawley, A. “Atomization.” *Encyclopedia of Materials: Science and Technology (Second Edition)*, Elsevier, 1 Jan. 2003, https://www.sciencedirect.com/science/article/pii/B0080431526000772.