Effects of Nozzle Geometry on the Near-Field Characteristics of a Liquid Jet

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Abstract

The present paper reports an experimental investigation on the effect of nozzle geometry on the near-field characteristics of a liquid jet discharging into a still environment at standard ambient conditions. The influence of nozzle geometry on jet flow is studied here by examining nozzle aspect ratio and angle of contraction. Liquid jet mean-velocity and turbulence intensity profiles as well as surface appearance are investigated in order to analyze the effects of these geometric nozzle parameters. The experimental results revealed that decreasing the nozzle aspect ratio generally flattens the velocity profiles, thus generating a less turbulent jet. Decreasing the contraction ratio tends to increase the level of turbulence. Also, increasing nozzle diameter appears to promote turbulence. The present study ultimately shed more light on the irrefutable relationship between nozzle geometry and the nature of the ensuing liquid jet.

Introduction

Modern industries, from agriculture to aerospace, employ liquid jets and sprays. Domestic applications include showerheads, garden hoses, and hair sprays, which are all examples of liquid jet discharges and breakups [1]. A spray-generating process, atomization, is important in combustion, agricultural pesticide applications, paint spraying, food processing, and numerous other gas-liquid heat/mass transfer applications. Furthermore, performance and pollution of engineering power plants such as diesel engines, gas turbines, and rocket engines are greatly dependant on the fuel spray characteristics. The sustainment of many existing technologies depends on the ability to gauge flow, and there is an ever-increasing need to improve accuracy and reliability in these measurements. Certain industries also require long, unbroken jets, unlike the atomization and spray related applications. The nonwoven textile industry is an example, which employs extended, high-speed water jets in fabric production. Research confirmed that energetic water jets can replace steel needles, which conventionally entangle fibres in a web. Utilization of water jets in this application, hydroentangling, results in superior quality materials and an improvement in production rates [2]. Another example concerns the lubrication of the elements of the bearing chamber of aero-engines for which a continuous unbroken oil jet is aimed [3].

Despite extensive research on the topic, the impact of various parameters has not been fully investigated and scientific understanding is still incomplete. Indeed, the effects of turbulence, geometry, ambient properties and liquid properties on flow characteristics are still less understood. Nozzle geometry and internal flow have been generally disregarded in classic early literature, contributing to confusion and a lack of a coherent body of information on the subject. For example, complete understanding of liquid jet breakup in cross flow [4] has not yet been established. Recent literature, however, suggests that nozzle geometry may significantly influence jet flow characteristics, as several investigators revealed that their experimental data and conclusions are highly sensitive to the nature of the nozzle employed (e.g., [4-5]). Recent studies (e.g., [6-10]) investigated the influence of nozzle geometry on fuel flow features and engine performance. Significant discrepancies were observed in the results, and it is not clear whether this is related to the degree of flow cavitation or attributed to nozzle geometry effects (e.g., [5]). Recently very good progress has been made on the relationship between the nozzle geometry and the ensuing jet characteristics, and relevant studies have been reviewed in [11].

Due to the significant impact of the topic with regards to modern industrial applications, and the present lack of complete understanding, it is important to fully investigate liquid jets and their relationship to nozzle geometry [11]. This objective can be fulfilled by gaining a better understanding of the relationship between nozzle geometrical parameters and jet behaviour, such as jet velocity and turbulence intensity profiles, discharge coefficient, the surface properties of the jet flow, and jet breakup. Therefore, the aim of the present study is to investigate the effect of nozzle geometry, such as the nozzle aspect ratio and angle of contraction, on the near-field liquid jet velocity, turbu-

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lence intensity, and jet surface appearance. A more comprehensive study that includes all nozzle geometric parameters and their effects on jet breakup and jet overall characteristics is in progress and will be reported in subsequent publications.

Experimental Test Facility and Methodology

The experimental test facility is depicted schematically in Figure 1. Compressed nitrogen pressurizes water in a 9-liter stainless steel tank. Water from the tank is delivered at pressures ranging from 10 to 60 psi through a stainless steel tube and discharged from the nozzle into still air at standard atmospheric conditions. The resulting jet is characterized by employing Particle Image Velocimetry (PIV) to determine the jet near-field instantaneous velocity from which the local mean-velocity and their corresponding turbulence intensity profiles are then determined. To illuminate the flow, the Nd-YAG 120 mJ pulse laser of 530 nm wavelength generates a laser sheet which passes through the jet's centreline. A 60 mm diameter Nikkor lens is fitted to a 12-bits high-resolution Dantec HiSense 4M digital camera to capture successive images of the jet. The seeding particles used in the experiments are H-H6S, silver-coated hollow glass spheres of 5 μm in diameter. PIV measurements are taken for a field of view of approximately 35.6 by 43.8 mm, and the images are processed and analyzed using FlowManager software. During processing, a 32 by 32 pixel interrogation window is used together with 50% overlap and moving average validation. Grid independence of the results is verified using a 64 x 64 pixel grid with 50% overlap. To ensure accuracy in tracking individual seeding particles in the flow and computing the velocity vectors, a sufficiently short delay period between the two successive frames is captured by the PIV system. This is guided by the conventional rule that suggests that individual particles travelling with a mean velocity should not displace more than ¼ of the interrogation area between the two captured frames. Therefore, under each velocity condition, a very conservative delay period is implemented in this experiment, and accuracy of tracking is further verified through visual analysis of the resulting images. Delay periods ranging from 8 to 30μs are implemented for the variety of jet exit velocities and nozzle geometrical conditions.

A high-resolution, high-speed imaging system was also used to freeze the jet flow and capture its general appearance and shape. This was achieved by using Dantec's NanoSense MkIII high-speed camera with a resolution of 1024 x 1260 pixel and a 250 W light source, with an exposure time set to 3 μs. This exposure time is selected because it is a compromise between obtaining a sufficiently detailed image of the jet and capturing enough light to illuminate the jet. For greater exposure times, the jet image becomes blurred and detailed surface features cannot be discerned. The field of view is set equal to that used with the PIV system (i.e., ≈ 43.8 mm).

A variety of nozzle geometries and jet exit velocities were tested. Preliminary experiments showed that a 4.3 cm field of view is sufficient (≈ 22*d* downstream from the nozzle exit) to capture the near-field jet characteristics induced by the nozzle geometry (see Figure 2). Jet velocity and turbulence profiles are acquired for three streamwise positions, shown in Figure 2. These jet locations examined are 0.1*d*, 11*d* (≈ 2.2 cm), and 20*d* (≈ 4.0 cm) downstream from the nozzle exit. Table 1 reports the various nozzle geometries tested in this experimental study. Nozzle aspect ratio ranges between 1 and 10, while constraction angle ranges between 60 and 120 degrees. Most nozzles have an exit diameter of 2 mm, while only Nozzle 1 has a diameter of 1 mm. Two surface qualities are also employed in the nozzle constriction zone: 3.2 and 6.4 μm (but results are not reported here). In order to study the effects of individual geometry parameters, only one of the nozzle geometry parameters is varied at the time. To assess the number of images required for obtaining representative data, a preliminary comparative study is performed by analyzing data sets of both 200 images and 100 images with the PIV system under identical test conditions representative of the experiments to be performed [12, 13]. It is determined that the relative difference between the two sets of results is found insignificant. Therefore, to minimize processing time, 100 images are used throughout the experiments. The total duration of PIV sampling time ranges between approximately 15 and 40 seconds, depending on jet speed (or delivery pressure) and diameter. Under each experimental condition, velocity and turbulence intensity profiles are determined at the aforementioned three jet's streamwise positions.

Results and Discussion

Effects of Nozzle Aspect Ratio

The results presented below revealed that the effect of aspect ratio on jet flow becomes more pronounced at higher jet pressures (i.e., higher exit velocities). An increase in the nozzle aspect ratio results in a more turbulent jet, and consequently flatter velocity profiles. Figure 3 displays the normalized mean-velocity profiles for three different nozzle's aspect ratios at two different (i.e., Start and Middle) jet locations, as shown in Figure 2. Normalized velocity profiles at station "Terminal" are not presented here for space limitations and more importantly they do not change significantly with respect to those at "Middle" station. Overall, relatively flat velocity profiles are observed for the largest aspect ratio examined here (i.e., Nozzle 8, AR=10), indicating a greater degree of turbulence. Consider the flow behavior at the Start jet location for a supply pressure of 60 psi, shown in Figure 3-1b, where it is obvious that the smallest aspect ratio results in the most parabolic velocity profile. Furthermore, it is noticeable that the two nozzles of higher aspect ratios are less laminar in nature (Nozzle 5, AR=4 and Nozzle 7, AR=6). The corresponding turbulence intensity profiles (not shown here for space limitations) confirm that the largest aspect ratio (AR=10) exhibits manifestly higher levels of turbulence intensity than the other two nozzle geometries (AR=4 and AR=6) examined here.

The jet images at a delivery pressure of 60 psi, as shown in Figure 4, confirm the qualitative analysis reported above. Nozzle 5 *(N5),* with the geometrically smallest aspect ratio (AR=4), exhibits less jet surface irregularities than the nozzles with greater AR. The jet downstream surface irregularities of nozzles with AR=6 and AR=10, respectively, suggest a significant interaction of the jet flow with the ambient, and hence result in a more turbulent flow. Thus, it might be concluded that jet turbulence can be promoted by increasing aspect ratio, as this trend becomes more apparent with increasing jet delivery pressure.

Effects of Nozzle Contraction Angle

The degree of nozzle contraction is a significant factor in determining liquid jet characteristics. As shown in Figure 5, as the contraction angle increases, the flow behaviour changes dynamically, dependant on the angle through which the flow is constricted. The experimental results at low pressures (less than 30 psi) reveal increasingly flatter velocity profiles as the contraction angle augments. The trend is especially apparent at the "Start" location, as shown in Figures 5a and 5b, which display the normalized mean-velocity profiles at 10 psi and 30 psi, respectively. These results are consistent with existing literature, which implies that larger contraction angles force the fluid to navigate through larger corners, promoting flow detachment from the centre line of the nozzle [11]. Liquid that has separated from the interior wall is more susceptible to cavitation, and hence ultimately promote turbulence. However, cavitation is not expected in this study due to the streamlining of the nozzles [12, 13].

At an increased pressure of 60 psi, the jet normalized mean-velocity profiles both at the "Start" (Figure 5c) as well as at "Middle" locations (not shown here for space limitations) reveal a dissimilar tendency than that observed at lower pressures. The normalized mean-velocity profiles of Nozzle 6, with the greatest contraction angle (CA = 120^o), is the most parabolic in nature, suggesting a more laminar flow than the nozzles with smaller contraction angles. It should be noted that this observation is unanticipated as it disagrees with the expectation of higher turbulence attributed to cavitation effects in larger contraction angle nozzles, as noted with the lower pressures. This discrepancy may be justified by the phenomenon of hydraulic flip. Hydraulic flip results from induced flow separation from the inside of the nozzle wall failing to reattach within the length of the nozzle's constriction region. This phenomenon explains why a more laminar jet is observed to exit into the ambient [11]; however, further investigations are required to clarify this issue.

Jet images of the three nozzles with different contraction angles at a typical delivery pressure of 30 psi (Figures 6a,b,c) support the observations deduced from the velocity profiles. As the angle of contraction increases, the jet surface is rougher, exhibiting increased jet surface disturbances especially near the nozzle exit. Figure 6f demonstrates the laminar character of the higher jet pressure flow (60 psi), with the largest contraction angle (CA=120^o), confirming the above quantitative observations concerning the occurrence of hydraulic flip.

Conclusion

The effects of nozzle geometry (e.g., aspect ratio and contraction angle) were particularly evident at high jet delivery pressures, ranging from 30 to 60 psi. In addition, geometric influence on the flow behavior was especially noticeable directly at the nozzle discharge (Start) location, before downstream aerodynamic forces disturbed the jet and initiated breakup (e.g., jet stripping). The geometric parameters examined were noted to influence jet velocity, turbulence intensity, and surface appearance. Jets with longer constriction regions, or greater aspect ratios, have greater wall surface area contributing to increased wall friction, promoting turbulence in the emergent jet. At high delivery pressures, larger contraction angles led to more parabolic velocity jet profiles, possibly explained by detached flow which undergoes hydraulic flip interior to the nozzle. Increased nozzle outlet area marginally increases the flatness of the velocity profile, suggesting an increase in the turbulent nature of the flow.

Acknowledgements

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Table 1. Nozzle geometric parameters.

Geometric Parameter		**Nozzle ID**							
		N1	**N2**	**N3**	**N4**	**N5**	**N6**	**N7**	**N8**
Diameter	**d (*mm*)**	2	1	2	2	2	2	2	2
Exit length	**L (*mm*)**	6	4	8	8	8	8	12	20
Contraction angle	**α (^{o})**	60	60	60	90	90	120	90	90
Surface roughness	**SR(*μm*)**	6.4	6.4	6.4	6.4	3.2	6.4	3.2	3.2
L/d	**AR**	3	4	4	4	4	4	6	10

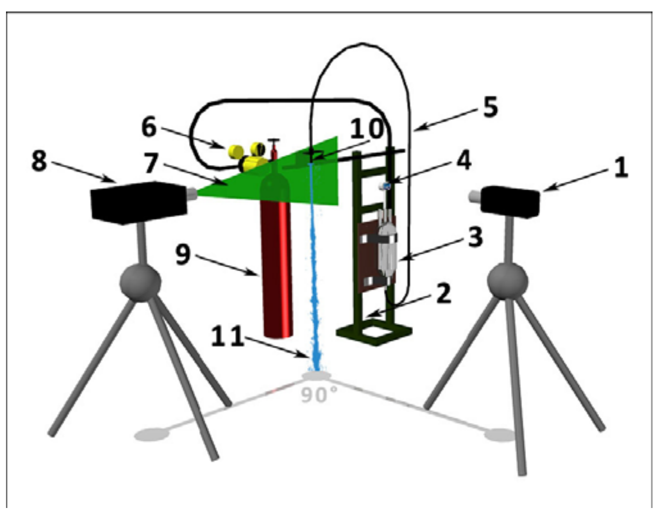

Figure 1. Schematic of the experimental setup. 1) Camera, 2) Support Frame, 3) Water Tank, 4) Pressure Gauge, 5) Tubing, 6) Pressure Regulator, 7) Laser Sheet, 8) Laser, 9) Compressed N_2 Tank, 10) Nozzle, 11) Water Jet.

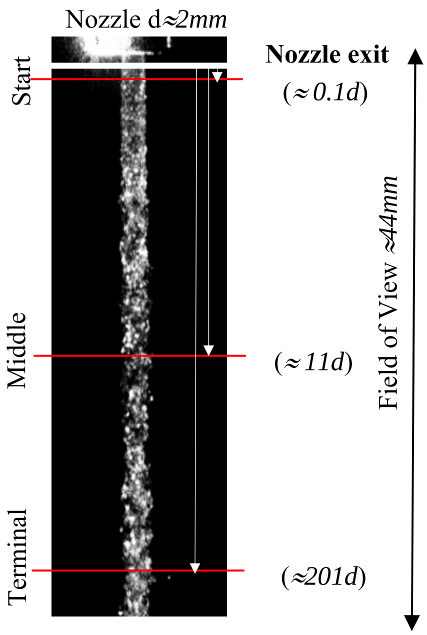

Figure 2. The three jet/stream locations where the velocity profiles were obtained.

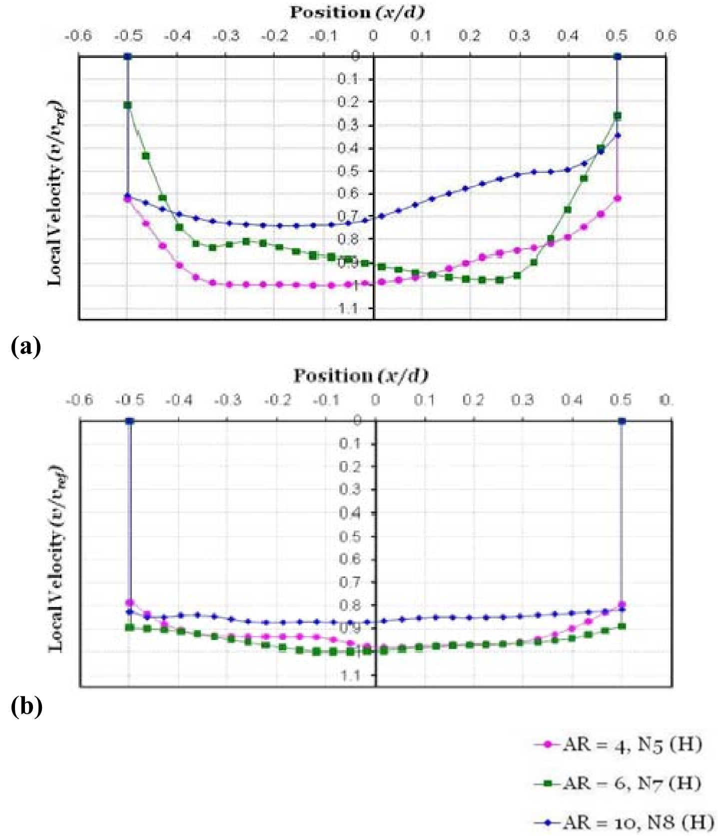

Figure 3. Effect of nozzle's aspect ratio on jet mean-velocity and the corresponding turbulence intensity profiles (jet delivery pressure = 60 psi). (a) Start location (v_{ref} = 23.9 m/s), (b) Middle location (v_{ref} = 25.2 m/s)

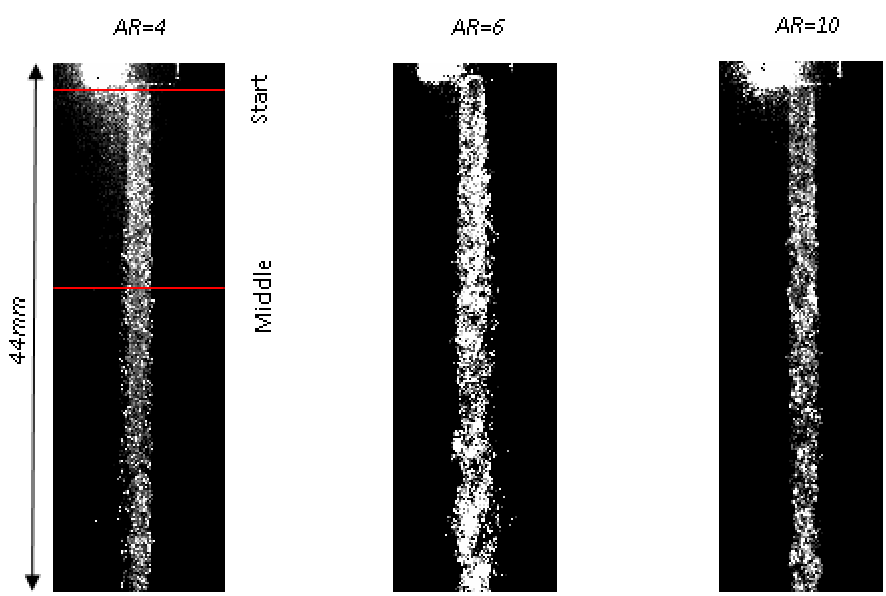

Figure 4. Jet images for different nozzle's aspect ratios (at 60 psi).

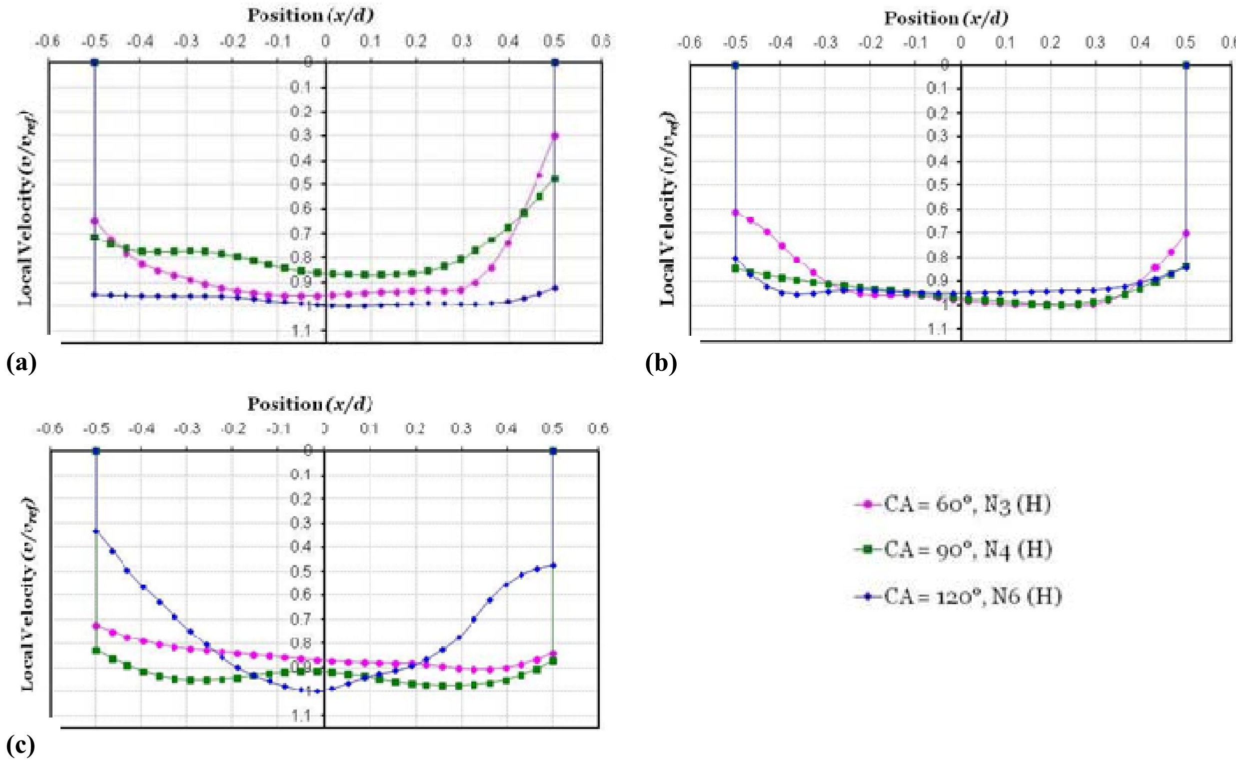

Figure 5. Effect of nozzle's angle of contraction on jet mean-velocity (Start location). (a) v_{ref} = 8 m/s and delivery pressure = 10 psi, (b) v_{ref} = 14.3 m/s and delivery pressure = 30 psi; (c) v_{ref} = 22.5 m/s and delivery pressure = 60 psi

Jet delivery pressure = 30 *psi* *(Figs. a, b & c)* **Jet delivery pressure = 60 *psi*** *(Figs. b, e & f)*

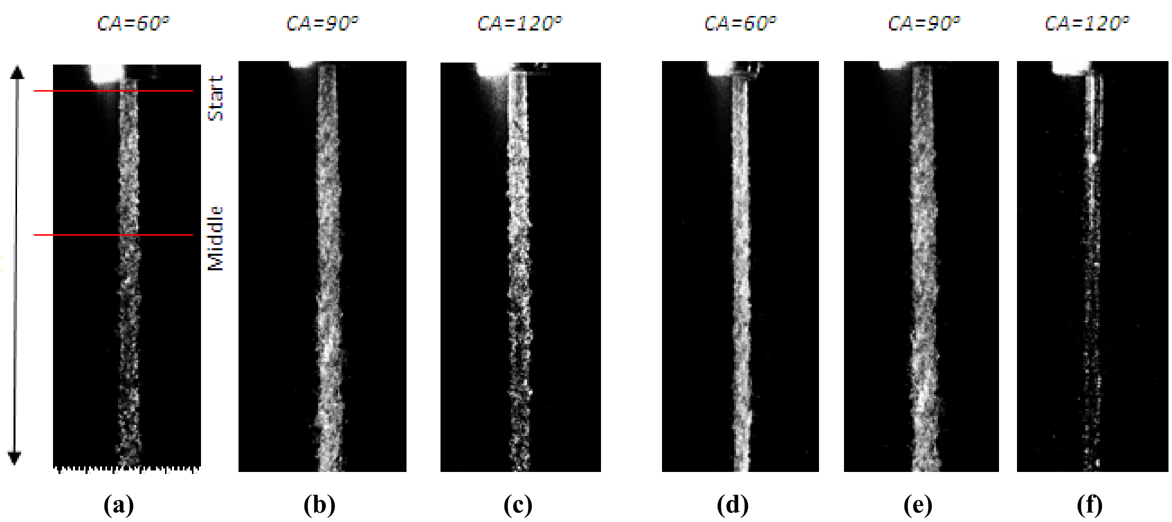

Figure 6. Jet images for different nozzle's contraction angles.