An experimental investigation of discharge coefficient and cavitation length in the elliptical nozzles

Sung Ryoul Kim*†, Kun Woo Ku*, Jung Goo Hong** and Choong Won Lee*
*† Department of Mechanical Engineering
Kyungpook National University
1370 Sankyuk-dong Buk-gu, Daegu, Republic of Korea
**Institute of Mechanical Engineering Technology
Kyungpook National University
1370 Sankyuk-dong Buk-gu, Daegu, Republic of Korea

Abstract

Cavitation in the nozzle is known to have influence on the liquid jet. In order to investigate the influence of cavitation, the experiment was conducted with a set of elliptical nozzles of approximately same area of cross section but varying orifice aspect ratio. Each of nozzle made of acryl for visualization. The measurements obtained for the elliptical liquid jet were compared with circular liquid jet. The flow rate increased with the injection pressure, and discharge coefficient decreased with the injection pressure. Especially the change of flow rate and decrease of discharge coefficients were generated with onset of cavitation. The injection pressure to start cavitation was 1bar regardless of any nozzle. The cavitation length for circular nozzle is longer than for elliptical nozzles in the same injection pressure. The spray angle has widest at the elliptical nozzle when the cavitation number is 1. And the spray angle at the elliptical nozzle has wider than at the circular nozzle.

Introduction

Spray combustion is widely used in many industrial applications such as diesel engines, gas turbine combustor, burner and so on[1]. Spray is strongly affected by atomization mechanism in diesel engine. Small SMD and wide spray angle had extended the surface area of droplet. Small SMD and wide spray angle are easy to evaporate and have the advantage in mixture formation. For these reasons, a number of studies have been conducted on the effects of the nozzle characteristics on the internal and external spray performances. Especially the result of the Gong yunyi et al[2] reported that the spray angle of the elliptic nozzle is much larger than that of the circular nozzle. And the SMD of elliptic sprays is smaller than that of the circular spray.

The elliptical nozzle studied by T.V. Kasyap[3] recently. The axis-switching process is visibly illustrated elliptical liquid jets at flow conditions beyond the transition regime. The amplitude of axis-switching is strongly dependent on the aspect ratio(a/b) of the nozzle. The axis-switching increased jet instability and got a shorter break-up length. So it makes large spray angle and small SMD. But this study concentrated on only external flow.

One of the factors that influence nozzle flow characteristic is a cavitation. Cavitation is generated by the liquid to bubble form in the low static pressure flow regions when the pressure is less than the saturated pressure[4]. Payri et al[5] reported that cavitation leads to an increase of the spray corn angle as well flow outlet speed. Sou et al[6] investigated using 2-D nozzle with two acryl plate and one stainless steel plate. They are classified 4 regimes according to internal flow: 1 – no cavitation, wavy jet; 2 – developing cavitation, wavy jet; 3 – super cavitation, spray; 4 – hydraulic flip, flipping jet. Liquid atomization near the nozzle exit depends on cavitation regime. And when the cavitation reached at the nozzle exit, the cavitation cloud leads to effect of jet formation due to the collapse of cavitation clouds. The strong turbulence induced by the collapse of cavitation near the exit plays an important role in ligament formation.

Stainly Cameron et al[7] investigated cavitation phenomena in a circular hole. They used acryl nozzle for visualization. They observed cavitation inside of nozzle hole using high speed camera. They analyzed the image of cavitation at nozzle exit by using high speed camera. The cavitation leads to increase turbulent kinetic energy(TKE) at the end of nozzle. And TKE had effected on the ligament formation.

K. Rananurthi et al[8] explained cavitation in terms of the discharge coefficient(C_d). In a nozzle, the discharge coefficient is the ratio of the mass flow rate at the discharge end of the nozzle to that of an ideal nozzle which expands an identical working fluid from the same initial conditions to the same exit pressure[9]. Small diameter of the nozzle gives higher discharge coefficient. The discharge coefficient for cavitation flows do not depend on Reynolds number. The orifice with an length to diameter ratio(l/D) of about 5 give enhanced distur-

†Corresponding author: frustrat@nate.com

bances in jet when the flow is cavitating. Especially hysteresis appeared at the aspect ratio is about 5. The discharge coefficient had a approximately fixed value after the hysteresis occur. It is the region of hydraulic flip.

The purpose of this study is to investigate the influence of discharge coefficient and cavitation at the different geometry of elliptical nozzle and circular nozzle. All nozzles were made of the acryl for visualization. And using the nozzle ratio of length to diameter is 4. The cavitation and spray angle were visualized using a CCD camera under the various conditions of the injection pressure and cavitation number.

Experimental apparatus and Methods

Experimental apparatus

A schematic of experimental setup is shown in Figure 1. The equipment consists mainly of a liquid injection system, measuring device and flow visualization system. Water at room temperature was discharged form nozzle into the ambient air by nitrogen tank through the surge tank. Liquid flow rate was measured using the flow sensor(Korea flow meter IND, KTM-800), the pressure in tank was measured using the pressure sensor(sensys, PSHE0020KCIG) and the injection pressure was measured using the pressure sensor(sensys, PSCD0010BCIG). The signal from the sensors was acquired by data acquisition board. A CCD camera(vieworks, VM-2M 35) and scope(delloscop, 3020) were used to take images of the cavitation and spray characteristic.

One circular nozzle and two elliptical nozzles of various aspect ratio(a/b) were used for study. The geometric details of the nozzles are given in Table. 1. Cross-sectional area of all nozzles was approximately same. All of nozzles were made of acrylic for internal visualization. Figure 2 illustrates the circular nozzle and elliptical nozzles used in the present study. Nozzles have a cylindrical chamber of diameter 15mm and length 40mm above orifice and are a sharp edge nozzle. Elliptical orifice has a major axis(a) and minor axis(b).

Experimental methods

Flow conditions of liquid jets were expressed in terms of non-dimensional numbers such as cavitation number(σ) and discharge coefficient (C_d).

$$\sigma = \frac{P_a - P_v}{\frac{1}{2}\rho V^2} \tag{1}$$

$$C_d = \frac{Q}{A_o\sqrt{\frac{2P_i}{\rho}}} \tag{2}$$

$$\text{Circumference of circle} = \pi \cdot D \tag{3}$$

$$\text{Circumference of ellipse} = 2a \cdot E(k) \tag{4}$$

$$E(k) = \int_0^{\frac{\pi}{2}} \sqrt{1 - (\frac{b^2}{a^2})^2 \sin\theta^2}\, d\theta \tag{5}$$

P_a is the ambient pressure, P_v is the vapour pressure, ρ is the liquid density, V is the liquid velocity which is equal to Q/A_o, μ is the liquid viscosity, Q is the mass flow rate by measured in flow sensor. P_i is the injection pressure, it is measured by pressure sensor in nozzle. A_o is the area of the nozzle orifice. The discharge coefficient is the ratio of the mass flow rate(Q) at the discharge end of the nozzle to that of an ideal nozzle. Circumference of ellipse calculated using matlab program. Flow rate was measured by the flow meter.

Results and Discussion

Flow rate and Discharge coefficient by injection pressure

The flow rate given in Figure 3 shows a monotonic increase with injection pressure. The trend of flow rate is increased with injection pressure for all nozzles. Characteristic of flow rate was different over 1bar with injection pressure in each nozzle. The flow rate was same under 1 bar(dotted line) for injection pressure but the flow rate after the line was different. Elliptical nozzle had lower flow rate than circular nozzle over 1bar for injection pressure.

The discharge coefficient with injection pressure is shown in Figure 4. The trend of discharge coefficient is deceased with injection pressure for all type of nozzles. When the injection pressure was 1 bar, the cavitation started in the nozzle. The cavitation was role of interrupting flow of fluid in the nozzle. And another dot lines indicated that the cavitation reached the exit of nozzle. Circular nozzle had higher discharge coefficient than the elliptical nozzle at the same injection pressure. E3 nozzle has a wider region of developing cavitation than that of E2 nozzle. E3 nozzle has a lower discharge coefficient at the same injection pressure than E2 nozzle. The length of circumference in ellipse has longer than circle. Therefore the elliptical nozzle has larger wetting area than circular nozzle. The cavitation developed between 1 bar and 2.5bar of injection pressure in elliptical nozzle, so the fluid has different surface of contact with cavitation at each nozzle. It has different shear stress between surface of contact with cavitation and wetting area of nozzle. This phenomenon is due to the difference of shear stress.

Cavitation length by injection pressure

Figure 5 shows the cavitation length with injection pressure. The cavitation was generated at 1bar for injection pressure. And cavitation was developed from nozzle inlet to outlet with injection pressure in each nozzle. The circular nozzle has longer cavitation length than the elliptical nozzle at the same injection pressure. The cavitation length reached the exit of nozzle at lower injection pressure in the circular nozzle. The bigger aspect ratio has shorter cavitation length in same injection pressure. The major axis has a longer cavitation length than in the minor axis. When the cavitation length reached at nozzle exit in a major axis, the cavitation disappears in a minor axis. The velocity profiles were not uniform in the cylindrical flow, because of shear stress[10]. The length of circumference in ellipse has longer than circle. And the elliptical nozzle has different radius of curvature at inlet of nozzle. Differences of shape, radius of curvature and circumference made different velocity profiles in the elliptical nozzle. Therefore the different velocity profiles made different cavitation length at major axis and minor axis.

Spray angle by the cavitation number

Spray angle was measured using the mean value of 20 images of spray. And the images were given the threshold value of 240 in image processing. Spray angles were as show in Figure 6. Figure 7 shows the spray angle with cavitation number(σ). Spray angle measured the region after the cavitation start. It was constant about 12~14° before the cavitation start, the spray angle increased after the start of cavitation. Especially when the cavitation length was the longest(cavitation reached at the nozzle exit), the jet has the widest spray angle. Cavitation number had approximately 1 in elliptical nozzle when the jet has the widest angle. The spray angle had the most wide angle(35°) in E3 nozzle when σ is 0.95, and the angle of spray has 31° in E2 nozzle when the σ is 0.99. But in circular nozzle, the widest spray angle got between 0.89 and 0.98 of cavitation number. And the widest angle of spray is 24° in the circular nozzle. Elliptical nozzle had a wider spray angle than circular nozzle. E3 nozzle had a wider spray angle than the E2 nozzle. Strong turbulence induced by the cavitation plays an important role in ligament formation[6]. Therefore the bigger aspect ratio enhanced instability of cavitation in ellipse nozzle. And the bigger aspect ratio will make strong turbulence near the exit of elliptical nozzle. It has different spray angle and spray characteristic in different nozzle geometry.

Summary

In this study, the effect of discharge coefficient and cavitation length in elliptic nozzle was investigated. The conclusions in this studied as follows :

1. The flow rate with injection pressure is increased, and discharge coefficient is decreased. The wetted area inside of nozzle has effect on the flow rate and discharge coefficient.
2. The onset of cavitation had a same injection pressure regardless of any nozzle. The circular nozzle has longer cavitation length than the elliptical nozzle at the same injection pressure. The bigger aspect ratio has shorter cavitation length in same injection pressure at the elliptical nozzle. The cavitation length reached at a nozzle exit in a major axis, the cavitation disappears in a minor axis. The different velocity profiles were made different cavitation length at major axis and minor axis.
3. Spray angle increased after the start of cavitation. The biggest spray angle appeared when the cavitation reached in nozzle exit. The cavitation number is 1 when the cavitation reached at nozzle exit. And the biggest spray angle had different between circular and elliptical nozzle.

Nomenclature

A	area of orifice [mm^2]
D	diameter of circular orifice [mm]
Q	mass flow rate of liquid [m^3/s]
P_i	injection pressure [N/m^2]
C_d	discharge coefficient
Pa	ambient pressure [N/m^2]
Pv	vapour pressure [N/m^2]
$E(k)$	complete elliptic integral of the second kind
a	length of the major axis [mm]
b	length of the minor axis [mm]
l	length of nozzle orifice [mm]
ρ	density of water [kg/m^3]

σ cavitation number
θ spray angle [degree]

References

[1] N. Tamaki, M. Shimizu, K. Nishida, H. Hiroyasu, *effect of cavitation and internal flow on atomization*, Atomization and Spray, 1998, Vol.8, pp179~197
[2] Gong Yunyi, Liu Changwen, Huang Yezhou and Peng Zhijun, *An Experimental Study on Droplet Size Characteristics and Air Entrainment of Elliptic Sprays*, SAE international, 1998.
[3] T.V. Kasyap, D.Sivakumar, B.N. Raghunandan, *Flow and breakup characteristics of elliptical liquid jets*, , International journal of Multiphase Flow, 2009, pp. 8-19.
[4] Lefebvre, A.H., *Atomization and Sprays*, Taylor&Francis, New York, 1989.
[5] Payri F., Bermudez V., Payri R., Salvador F. J., *The influence of cavitation on the internal flow and the spray characteristics in diesel injection nozzle*, Fuel, 2004, pp419-431.
[6] Akira Sou, Shigeo Hosokawa, Akio Tomiyama, *Effects of Cavitation in a Nozzle on Liquid Jet Atomization*, , International journal of Heat and Mass Transfer Vol.50, lss. 17-18, 2007, pp. 3575-3582.
[7] Stanley, Cameron, Rosengarten, Gary, Milton, Brian, Barber, *Investigation of cavitation in a large-scale transparent nozzle*, FISITA 2008 Student Congress, 2008.
[8] K.Ramamurthi, K. Nandakumar, *Characteristics of flow through small sharp-edged cylindrical orifices*, Flow Measurement and instrumentation 10, 1999, pp. 133-143.
[9] Wikipedia[online]. [cit. 2010-04-27]. http://en.wikipedia.org/wiki/Discharge_coefficient.
[10]Munson, Young, Okiishi, *Fundamentals of fluid mechanics*, john Wiley & Sons, 1998, pp459-465

Table 1. Geometrical details for the nozzles

Nozzle type	Major axis, a (mm)	Minor axis, b (mm)	Aspect ratio, a/b	Area, A (mm^2)	Circumference of nozzle (mm)
Circular (C)	5.083	5.036	1.009	20.10	15.89
Elliptical 2 (E2)	7.016	3.620	1.936	19.95	17.13
Elliptical 3 (E3)	8.370	2.916	2.870	19.17	18.77

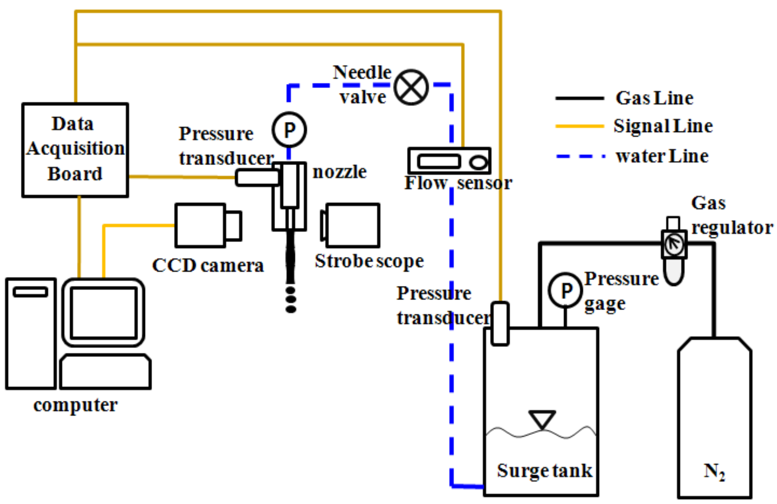

Figure 1. Experimental setup

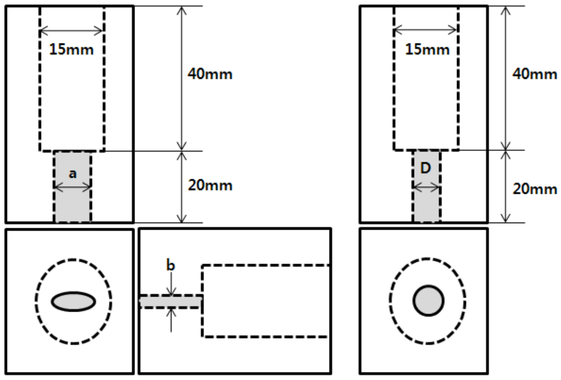

Figure 2. Schematics of test nozzles. The elliptical nozzle had major and minor axis. The circular nozzle has only diameter.

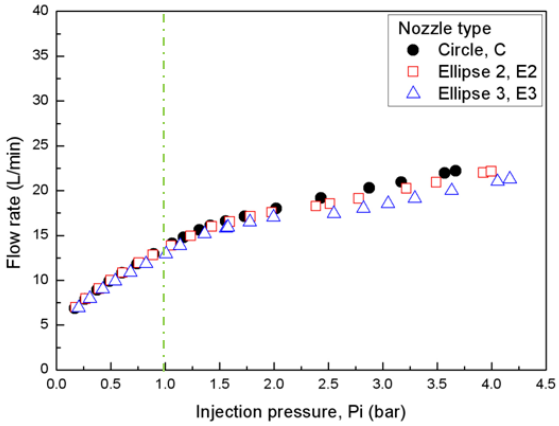

Figure 3. Variations of flow rate with injection pressure for different nozzles.

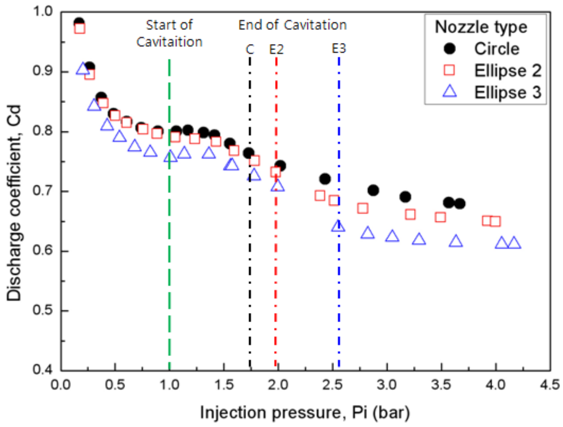

Figure 4. Effects of injection pressure on discharge coefficient.

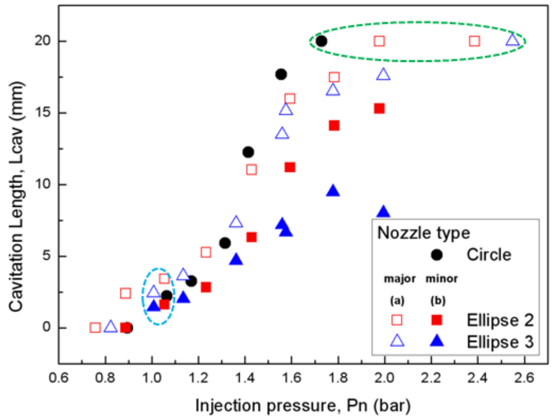

Figure 5. Variations of cavitation length with injection pressure.

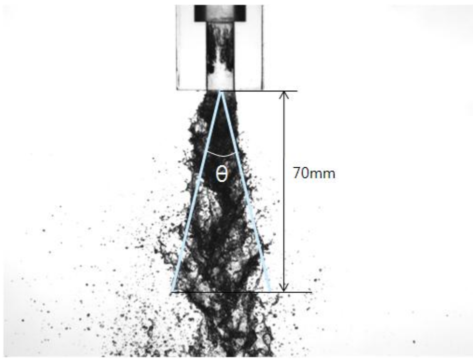

Figure 6. Spray angle, θ.

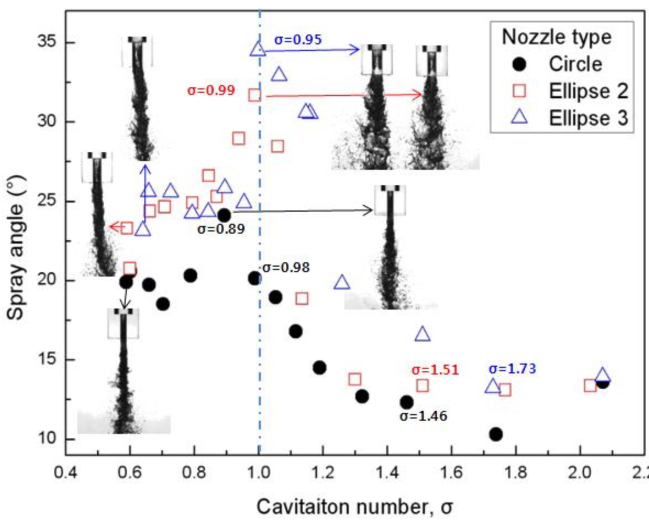

Figure 7. Effects of cavitation number on spray angle at major axis.