International Journal of Heat and Fluid Flow 29 (2008) 1001–1009

Contents lists available at ScienceDirect

International Journal of Heat and Fluid Flow

journal homepage: www.elsevier.com/locate/ijhff

Effect of cavitation in nozzle orifice on the diesel fuel atomization characteristics

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A R T I C L E I N F O

Article history:
Received 13 September 2007
Received in revised form 1 February 2008
Accepted 19 March 2008
Available online 7 May 2008

Keywords:
Atomization
Cavitation
Fuel injection
Phase Doppler particle analyzer (PDPA)
Sauter mean diameter (SMD)

A B S T R A C T

This study was conducted to investigate the effect of cavitating flow on the diesel fuel atomization characteristics in nozzles of different length to width (*L*/*W*) ratios.

In order to obtain the atomization characteristics due to the cavitation in the nozzle flow, the visualization of cavitation was performed by flow visualization system, and atomization characteristics such as Sauter mean diameter (SMD) and droplet mean velocity was determined by using a particle analysis system.

The results of this study show that the cavitation flow in the nozzle can be observed when the discharge coefficient is within the range from $C_d = 0.709$ to 0.8312 in case of $L/W = 1.8$, and $C_d = 0.5793$ to 0.7705 in case of $L/W = 2.7$. Based on the experimental results, it can be said that the cavitation generated in the nozzle enhances the fuel atomization performance and the longer nozzle orifice length induces more fuel atomization.

1. Introduction

In a diesel engine, the design of fuel injection nozzle is an important factor for the improvement of the combustion performance and reduction of emissions because nozzle geometry influences the spray characteristics and air–fuel mixing in the engine (Gavaises and Andriotis, 2006; Payri et al., 2006). For these reasons, a number of studies have been conducted on the effect of the nozzle characteristics on the internal and external spray performances (Heimgärtner and Leipert, 2000; Kurachi et al., 2001; Gupta et al., 2000; Hasegawa et al., 1998).

One of the factors that influence nozzle flow characteristics is cavitation. Cavitation is generated from the liquid to bubble form in the low static pressure flow regions when the pressure is less than the saturated pressure (Lefebvre, 1989). Cavitation that is a formation of gas and vapor bubble in the nozzle filled with liquid has a great influence on both fuel injection and performance of the engine. Cavitation that is formed at the entrance of a flow concentration also affects the disintegration phenomena of a liquid jet after fuel injection. This aspect of cavitation has been the topic of many recent studies with regards to diesel fuel cavitation (Roth et al., 2005; Ganippa et al., 2001; Chaves et al., 1995).

Payri et al. (2004, 2005) reported that cavitation leads to an increase of the spray cone angle as well as flow outlet speed, and measured the spray momentum in order to explain the effects of nozzle geometry. Badock et al. (1999) investigated the cavitation phenomena in a real-size diesel injection nozzle hole. They observed cavitation films and the core of the flow inside of the spray hole using a light sheet method. Computational and experimental studies of a variable nozzle flow were performed by Kim et al. (2006). They reported that the discharge coefficient of a nozzle is a function of the Reynolds number and increases as the equivalent nozzle diameter increases. Using a laser light sheet, Soteriou et al. (1995) studied the internal flow structure in a scaled-up plain orifice nozzle and observed incipient cavitation at three distinct locations, namely, a separated boundary layer inner region, a main stream flow, and an attached boundary layer inner region. Further, a study by Arcoumanis et al. (1998) measured the pressure distribution in the nozzle sac and found that cavitation at the hole inlet is dependent on both nozzle sac geometry and inlet hole configuration.

Although cavitation within the nozzle orifice has been studied extensively (Jia et al., 2007; Koivula and Ellman, 1998; Schmidt et al., 1997, 1999), the effect of cavitation on the internal flow and external spray performance are not that well understood especially in the case of diesel fuel. One area of particular interest is how nozzle cavitation affects the fuel atomization performance due to the difficulty of making the appropriate measurements. Hence, the enhancement of fuel atomization characteristics by cavitation has not been cleared yet.

The aim of this study is to investigate the influence of cavitating flow in the different length to width (*L*/*W*) ratio nozzle on the diesel fuel atomization characteristics in terms of Sauter mean diameter (SMD), droplet mean velocity, and counted percentage of droplets, respectively. At the same time, the macroscopic characteristics

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doi:10.1016/j.ijheatfluidflow.2008.03.014

Nomenclature

A	orifice cross-sectional area (mm^2)
C	coefficient
D	orifice diameter (mm)
K	cavitation number
$\dot{m}$	flow rate (l/min)
L	length (mm)
P	pressure (MPa)
R	radial distance (mm)
V	injected fuel velocity (m/s)
W	orifice width (mm)
Z	axial distance (mm)
Greek	
σ	surface tension (N/m)
μ	viscosity (Ns/m^2)
ρ	density (kg/mm^3)
Subscripts	
b	back
d	discharge
v	vapor
inj	injection
w	wall

were analyzed under various conditions in terms of Weber number (*We*), Reynolds number (*Re*), Cavitation number (K) and discharged coefficient (C_d).

2. Experimental apparatus and procedure

2.1. Experimental apparatus

This work was performed to investigate the effect of nozzle cavitation on the fuel atomization performance in nozzles with different L/W ratios. Fuel cavitating flow was observed in the flow visualization system, as shown in Fig. 1, which is composed of a test nozzle, image acquisition system and fuel supply system. The shadowgraph method was used to explore the inside nozzle flow and the disintegration phenomena of outside spray behavior by using a high resolution ICCD camera (Dicam-PRO, The Cooke Corp.) and a spot lamp as a light source. The flow images were stored automatically to a PC installed image grabber. The fuel tank was pressurized by nitrogen gas for fuel spray, and a circulation pump (PW-200 M, WILO) was installed to supply the injected fuel from the fuel receiver to the fuel tank. The flow rate meter (A109LMA, GPI) was equipped to obtain the instant flow rate, and the injection pressure was obtained from a pressure gauge located at the entrance of the test nozzle.

As also can be seen in Fig. 1, a droplet measuring system for the analysis of the cavitation flow effect on the droplet mean diameter, droplet mean velocity, and counted percentage of droplets was comprised of a fuel supply system including the test nozzle, a transmitter with an Ar-ion laser, and a receiver that was synchronized with the signal and droplet analyzer. A laser beam was split and the four resulting beams crossed each other at a specified angle. The four beams are coherent to each other and make the control volume in their intersection. If a particle traverses the control volume, it scatters the light, and the four components of scattered light have different Doppler signals. Therefore, at the surface of the photo-detector, the four light components interfere, resulting in a pulsating light intensity. Based on the data rates and the signal intensity, the output of the Ar-ion laser and PMT (photo-multiplier)

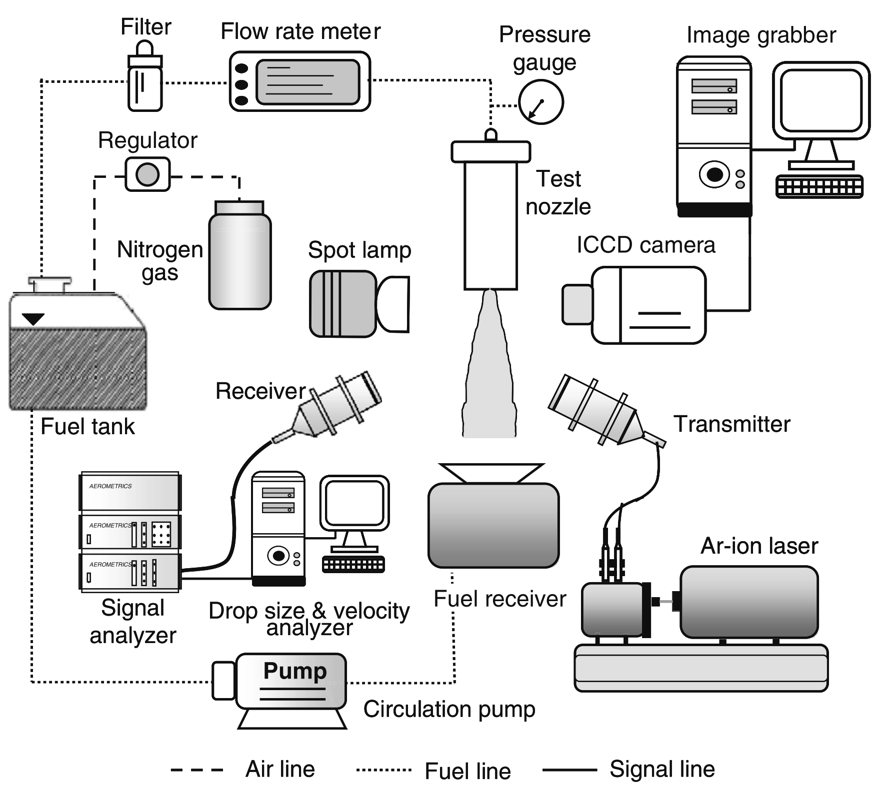

Fig. 1. Schematics of flow visualization and PDPA measuring system.

Table 1
Spray visualization and PDPA measuring system specifications

Spray visualization system	Light source	Spot lamp
	Resolution	1280 × 1024
Phase Doppler particle measuring system	Light source	Ar-ion
	Wave length	514.5 nm, 488 nm
	Focal length	500 mm for transmitter
		250 mm for receiver
	Collection angle	30 °

voltage were determined to be 700 mW and 550 V, respectively. The detail specifications of flow visualization and droplet measuring system are listed in Table 1.

The different nozzle geometries with two-dimensional rectangular cross-section and orifice were made by the transparent acrylic resin to simplify the optical observation, as shown in Fig. 2. The visualization of the internal and external nozzle flow was conducted in front of the nozzle. The nozzle width was fixed at 5 mm, however, the two nozzle lengths were used, 9 and 13.5 mm for considering the scale of real-size nozzle. The 5 mm × 9mm nozzle had a length to width ratio of 1.8, and the 5 mm × 13.5 mm nozzle has a width to length ratio of 2.7. By adjusting the focal plane, the internal and external spray flow could be observed by high resolution ICCD camera.

2.2. Experimental procedures

Diesel fuel was applied as the test fuel for the study of the effect of nozzle cavitation on the fuel atomization and external nozzle flow characteristics. The properties of diesel fuel are listed in Table 2.

The fuel cavitating flow inside the nozzle and its effect on the spray behaviors are investigated under various test conditions, as shown in Table 3. In order to investigate the propensity of nozzle cavitation, the cavitation number (K) that is the ratio of the pressure difference between vapor pressure (p_v) and back pressure (p_b) as defined by the the following equation was analyzed:

$$K = \frac{P_i - P_v}{(\rho V^2/2)} \tag{1}$$

where P_i, ρ, and V mean the injection pressure, fuel density and injection velocity, respectively.

The nozzle discharge coefficient (C_d) is one of the main factors in the design of the engine injector. From this point of view, it can be expected that the discharge coefficient changes due to cavitating flow. The discharge coefficient (C_d) of a nozzle orifice is defined by the following equation:

$$C_d = \frac{\dot{m}_F}{A\sqrt{2(\Delta P \cdot \rho)}} \tag{2}$$

Table 2
Test fuel properties

Fuel	Diesel
Temperature (K)	293
Density (kg/m^3)	830
Surface tension (N/m)	0.278
Viscosity (Ns/m^2)	0.00223
Vapor pressure (MPa)	0.00128

Table 3
Experimental conditions

Flow visualization	Nozzle L/W ratio		1.8, 2.7
	Injection pressure (MPa)		0.13–0.45
	Ambient pressure (MPa)		0.1
	Ambient temperature (K)		293
	Reynolds number (Re)		7040–32644
PDPA experiments	*Injection pressure* (MPa)		
		L/W = 1.8	L/W = 2.7
	Turbulent flow region	0.16	0.2
	Cavitation region	0.3	0.35
	Hydraulic flip region	0.42	0.47

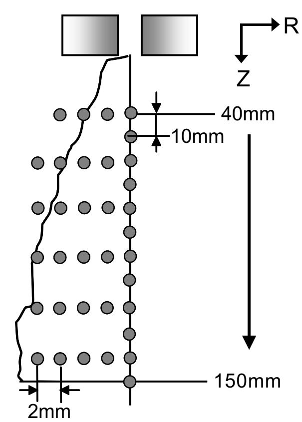

Fig. 3. PDPA analysis measuring points.

where $\dot{m}_F$, A, and ΔP indicate the flow rate of fuel, orifice cross-sectional area, and pressure drop at the nozzle, respectively. The definition of flow rate is the discharged liquid fuel mass during a given period of time.

The results of cavitation number (K) and discharge coefficient (C_d) obtained from the above equations, the flow characteristics was clarified as considering the Reynolds number ($Re = \rho VD/\mu$)

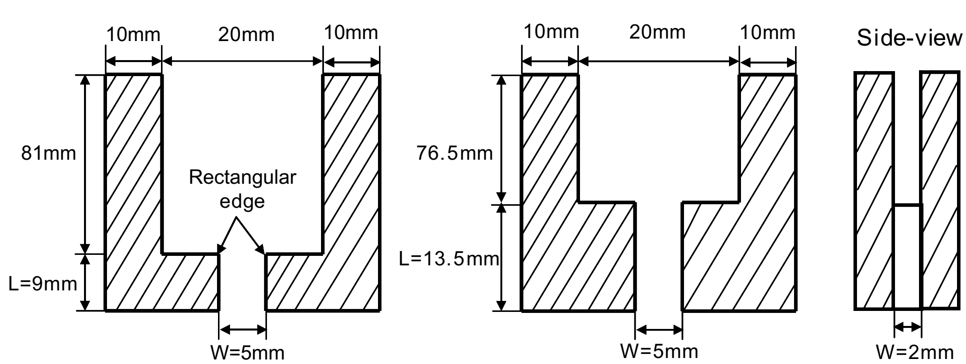

Fig. 2. Test nozzle specifications.

and Weber number (We $= \rho V^2 D/\sigma$), where σ is the surface tension of fuel droplets. Based on the results from the flow visualization experiments, the PDPA measurements were conducted at each injection pressure that shows different flow characteristics.

The measuring points of PDPA system are shown in Fig. 3. In order to obtain the fuel spray atomization characteristics after cavitation formed, the measuring points are selected from 40 mm to 150 mm at 10 mm intervals axially and at 2 mm intervals radially. For the time resolved atomization data, 50,000 droplets were captured and averaged at each measuring points. The representative SMD of injected fuel droplets was determined by averaging the detected droplets at all of the measurement points in a specified period of injection time with 0.1 ms of time steps under the continuous flow condition.

3. Results and discussions

3.1. Nozzle cavitating flow characteristics

The large rounded orifice inlet induces the decrease of cavitating flow region because it increases the outlet flow velocity and the discharge coefficient (Lefebvre, 1989; Payri et al., 2002). In this point of view, this study was conducted with rectangular orifice inlet that has 1.8 and 2.7 of width to length ratios to investigate the effect of the L/W ratios on the formation of cavitation in the nozzle and the external flow behaviors.

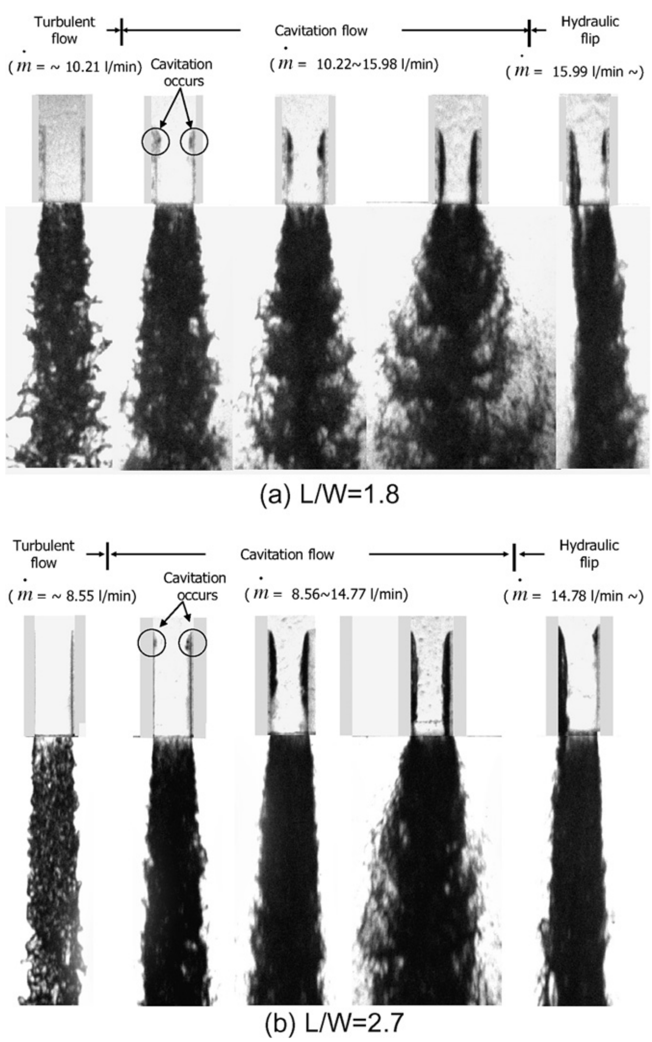

Fig. 4. Nozzle flow characteristics in a different L/W ratio.

Fig. 4 shows the nozzle cavitating behavior of both L/W ratios. Fig. 4a shows that the fuel flow rate increases as the injection pressure increases for 1.8 of length to width ratio. The cavitation bubbles are generated at 10.22 l/min of flow rate, and these cavitating forms are become larger as the flow rate increases from 10.22 l/min to 15.98 l/min. It can be also seen that as a cavitating form develops along the nozzle wall, the injected spray shape has a wider angle. Finally, at the flow rate of 15.99 l/min, the nozzle flow characteristic show flip behavior as illustrated in Fig. 4a. This phenomena can also be seen when $L/W = 2.7$, as shown in Fig. 4b. However, as the length to width ratio increases to 2.7, the cavitation bubbles and hydraulic flip occurs at higher injection pressure than they occur when $L/W = 1.8$. Moreover, the spray flow shape is not much wider although the cavity is fully developed in the nozzle orifice because the axial flow movement to the downstream could be strong in the long L/W ratio.

Based on the results of cavitating flow obtained from the flow images, the classification of cavitating flow can be divided into three regions, namely, turbulent flow region, cavitating flow region, and hydraulic flip region (Sarre et al., 1999). In the turbulent flow region, the static pressure in the concentration regions becomes lower than saturated pressure of the fuel, and cavitation bubbles appear at the edge of orifice as the injection pressure and flow rate are increased. In the cavitating flow region, the cavitation reached upstream of the nozzle exit; however, it collapses prior to fuel injection. These results can make the wider spray shape, and as a result, it can be said that the fuel atomization may have been improved in this region. In the hydraulic flip region, the cavitation bubbles reach the nozzle exit and were issued from the nozzle exit without being attached to the nozzle wall. In this case, the static pressure at the entrance of orifice reached to the back pressure in the nozzle outer region.

3.2. Effect of length to width ratio on the cavitating flow

As mentioned before, the increase of injection pressure induces an increase of flow rate. From the visualized flow images, three distinct flow regions can be seen in Fig. 5. Fig. 5 shows the relationship between injection pressure and flow rate of both L/W ratios. Moreover, when L/W is 1.8, flow rate decreased instantly in the hydraulic flip region. In addition, it can also be seen that the cavitating bubble is generated at the higher injection pressure in long L/W ratio. Fig. 6 shows the comparison of cavitation number in a different L/W ratio. The cavitation number is defined as the ratio of pressure differential between up and down positions to

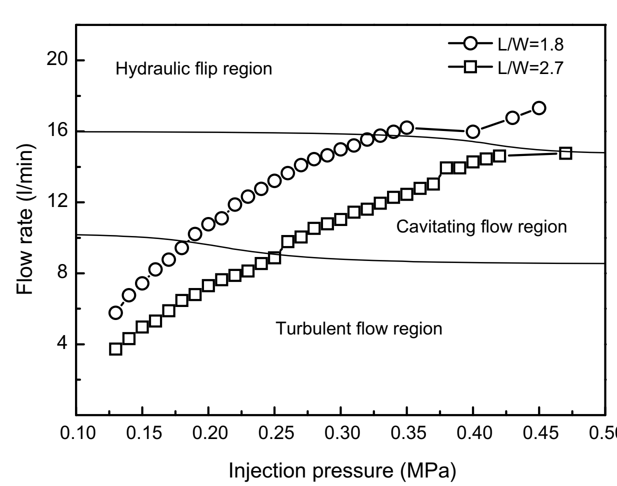

Fig. 5. Relationship between flow rate and injection pressure.

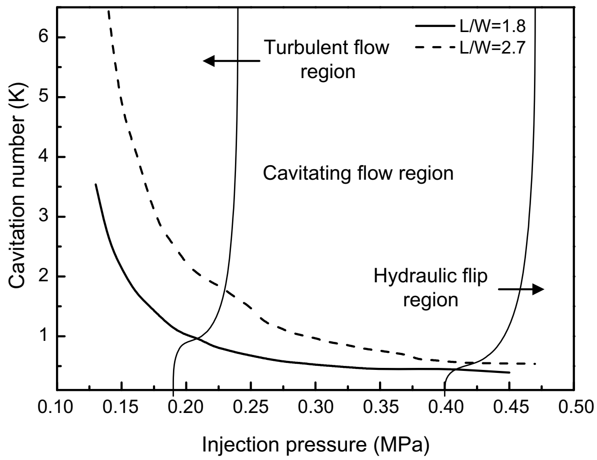

Fig. 6. Comparison of cavitation number in a different *L*/*W* ratio.

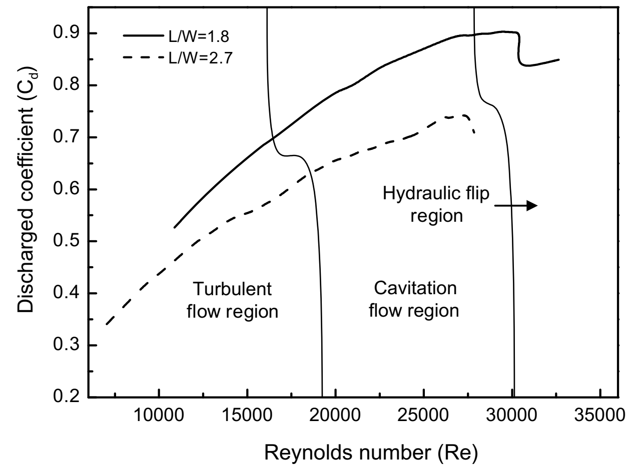

Fig. 8. Discharge coefficient in different *L*/*W* ratio.

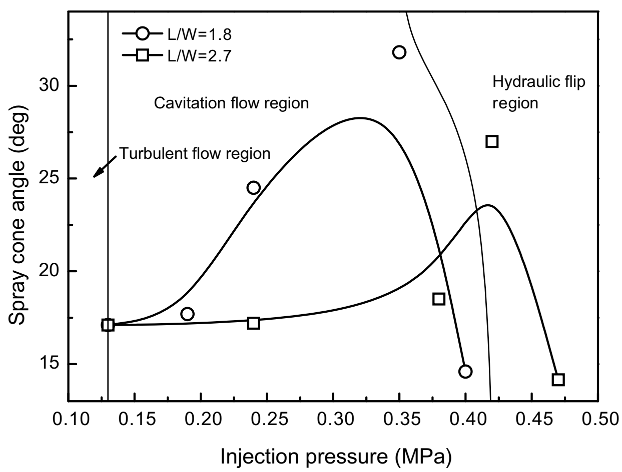

Fig. 7. Comparison of spray cone angle in different *L*/*W* ratio.

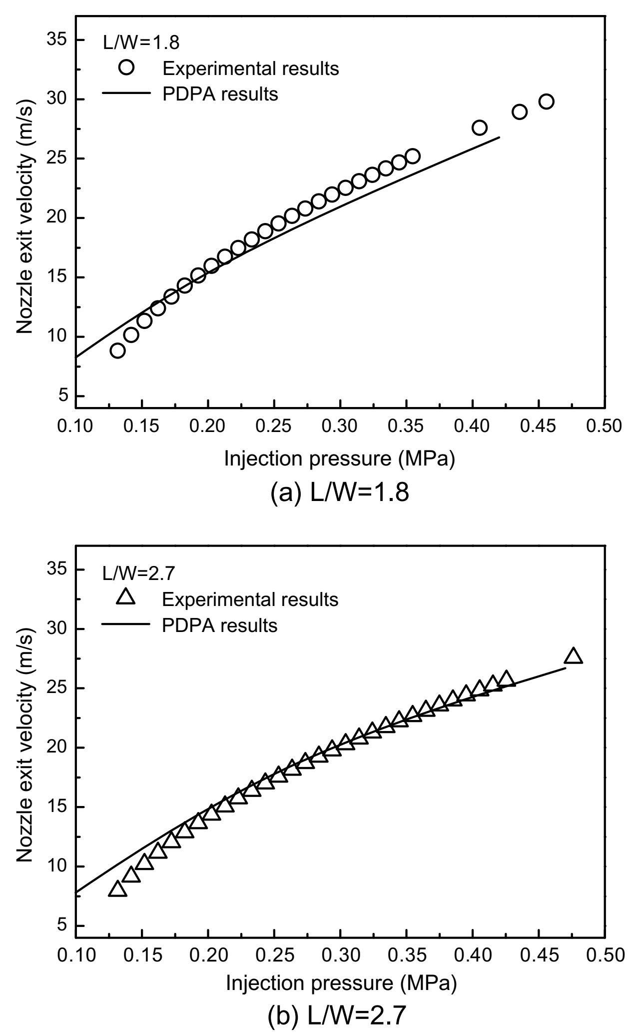

Fig. 9. Comparisons of nozzle exit velocity between experimental and PDPA results.

downstream pressure and indicates cavitation propensity. In general, the cavitation number decreases as the injection pressure increases and it is inversely proportional to the square of the velocity, as shown in Eq. (1). Fig. 6 is a good illustration of these characteristics of cavition number. The cavitation can not be observed when the cavitation number is larger than 1.13 because it is turbulent flow. From 0.46 to 1.13 of cavitation number, cavitation is generated and developed along the nozzle orifice, and the flow characteristics change to the hydraulic flip characteristics in the range under the 0.46 of cavitation number. On the other hand, when *L*/*W* is 2.7, the cavitation occurs when the cavitation number is 1.61, increased in the range from 0.54 to 1.61 of cavitation number, and hydraulic flip occurs within the range of 0.54 of cavitation number.

Fig. 7 illustrates the comparison of spray cone angle at each *L*/*W* ratio. In this figure, the flow regions were divided by injection pressure. As can be seen in this figure, in case of $L/W = 1.8$, the spray cone angle is larger than those of $L/W = 2.7$ in a whole injection pressure range. As the injection pressure increases, the flow changes from turbulent flow to cavitation flow, and the spray angle increases. It shows the maximum values, and the spray cone angle decreases dramatically due to the hydraulic flip characteristics. From these results, it can be said that the small *L*/*W* ratio induces the wider spray area, and it can lead to the fine droplet breakup process. In case of $L/W = 2.7$, the axial flow momentum to the downstream was stronger than that of $L/W = 1.8$ due to the longer nozzle length, and it makes small spray cone angle.

Generally, the important parameters influenced on the discharge coefficient are Reynolds number, length/diameter ratio, injection pressure differential, ambient gas pressure, and cavitation (Lefebvre, 1989). Fig. 8 shows the relationship between the discharge coefficient and the Reynolds number. This figure shows that the discharge coefficient generally increases with the increase of Reynolds numbers, and have a maximum value at a Reynolds number of around 30,000. Beyond this point, the discharge coefficient remains almost constant. As shown in Fig. 8, the discharge coefficient in the cavitation flow region at $L/W = 1.8$ is high because the flow rate is higher than $L/W = 2.7$. This can be said that the liquid jet formed at vena contracta has no time to re-expand and fill in the nozzle due to the short nozzle length. In the case of $L/W = 2.7$, the jet expands in the nozzle and the discharge coefficient decreases due to the low flow rate. It can be assumed that further increase in L/W ratio will reduce the discharge coefficient due to increase of frictional loss.

3.3. Effect of nozzle cavitation on the fuel atomization

Fuel atomization as an extension of the surface area of the fuel droplet is an important factor in the design of diesel engine. In this point of view, the influence of nozzle cavitation on the fuel atomization was investigated in terms of overall SMD values, velocity, and counted percentage of droplets distributions. At first, the uncertainty of experimental data should be clarified for the proof of the PDPA accuracy. In this study, the data acquisition rate and valid percent of measurement date were considered. In the vicinity of nozzle, the data rate is lower than at the other points because the fuel flow jet is not fully atomized in that region. Therefore, PDPA measurement conducted from 40 mm of axial distance. Data acquisition rate increases with the increase of the axial distance from the nozzle, and the data valid percent of PDPA acquisition is greater than 90% in all flow regions. Based on these results, it can be said that the experimental results from the PDPA system are reliable in this study.

Fig. 9 compares the nozzle exit velocity from the instant flow rate meter and PDPA experiments. In this study, the nozzle exit velocity can be defined as the ratio of the instant flow rate to nozzle cross-sectional area. On the other hand, PDPA results are the velocity from the different direction component vectors of droplets that obtained by Doppler signal. As shown in Fig. 9, the results from the instant flow rate meter and PDPA results are in good agreement. When L/W ratio is 2.7, the nozzle exit velocity is a little lower than when $L/W = 1.8$ at the same injection pressure because the flow resistance and wall friction in the nozzle orifice increase with increasing L/W ratio. Moreover, hydraulic flip may induce an instantaneous velocity drop because the nozzle orifice area decreases as shown in Fig. 4.

The influence of the Reynolds number and Weber number on the cavitation number was investigated, as shown in Fig. 10. In this figure, experimental and PDPA cavitation numbers were obtained by using the measured velocity from the flow rate meter and PDPA

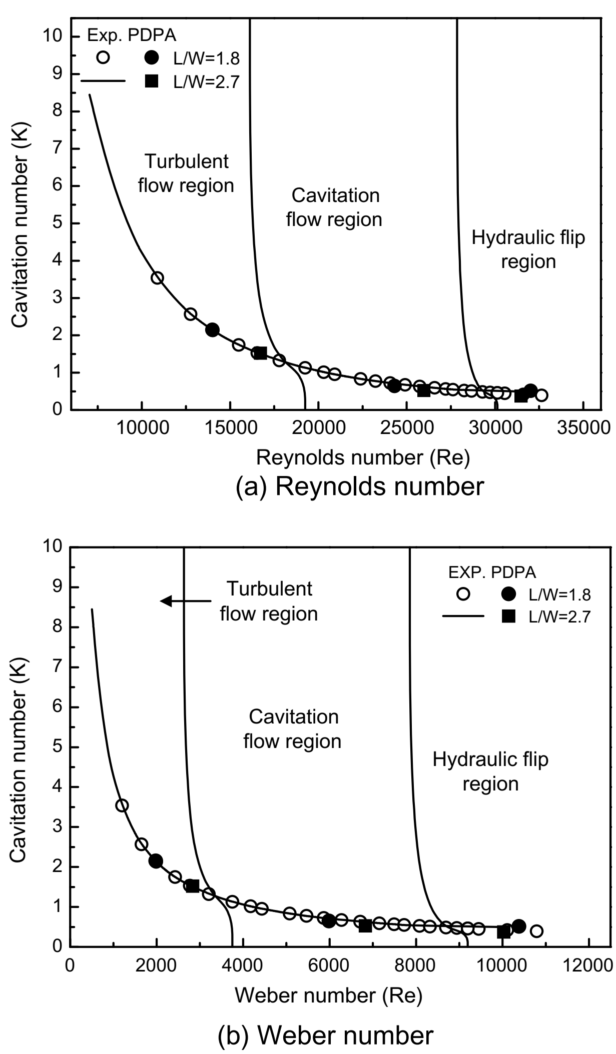

Fig. 10. Classification of cavitating flow in accordance with Reynolds number and Weber number.

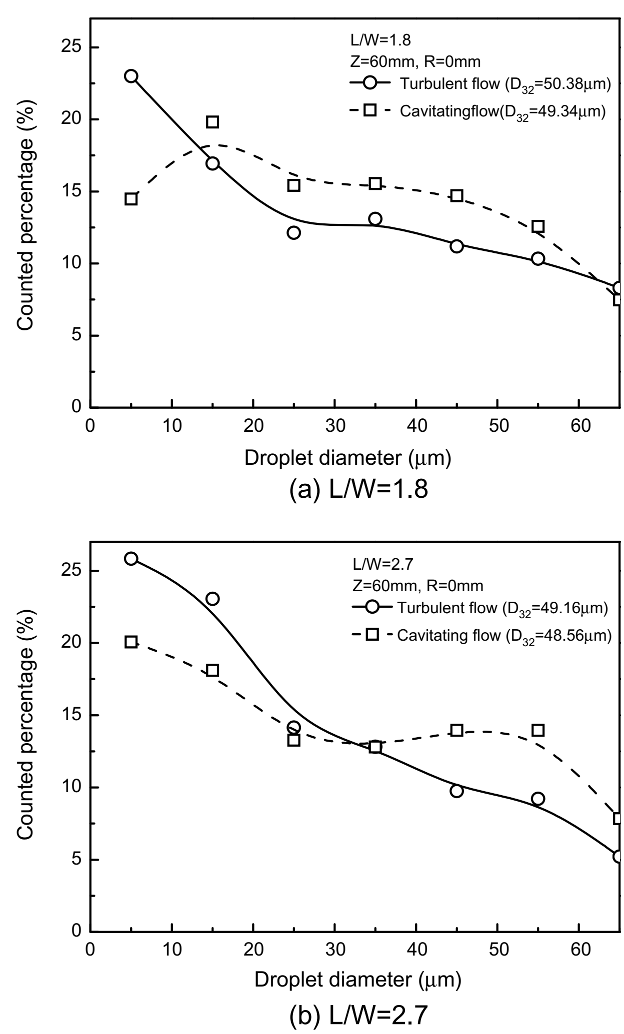

Fig. 11. Effect of flow characteristics on counted percentage of detected droplets.

system, respectively. These figures show that the cavitation number decreases exponentially with increases in the Reynolds and Weber numbers. In the turbulent flow region, the cavitation number decreases dramatically. In the cavitation flow region, the cavitation number remains relatively constant. Moreover, the cavitation numbers from the PDPA results are in agreement with the flow rate results.

From the droplet measurements, droplet diameter and velocity at each measuring point for the detected droplets can be obtained. Fig. 11 shows the effect of cavitating flow on the counted percentage of droplets at 60 mm of axial distance. When the flow characteristics change from turbulent flow to cavitating flow, the counted percentage of droplets that has a large diameter increases for both *L*/*W* ratios. Basically, the droplet measuring system assumes that perceived droplets have a perfectly circular shape. This means that the cavitating flow enhances the droplet breakup, and creates more small sized droplets. Therefore, a large number of droplets are distributed in the control volume which results in more droplets being sensed during cavitating flow.

Fig. 12 shows the time resolved overall SMD distributions for when $L/W = 1.8$. The overall mean values means the accumulations for all droplets captured at all measuring points at a specific time. The overall SMD at each flow region remains almost constant as the axial distance is increased. On the other hand, SMD in the cavitating flow is smaller than that of turbulent flow. The SMD distribution according to the radial distance shows the same trend. These results can also be seen in Fig. 13 that illustrates the case of $L/W = 2.7$. As shown in this comparison, the SMD is lower than that of turbulent flow region at *L*/*W* ratio = 2.7. These results show that the cavitation could be the dominant factor to increase the fuel atomization. Generally, when the cavitation bubbles are broken, the divergence of the bubble breakup energy which was stored on the surface of bubble affects the fuel atomization. Therefore, it can be said that the higher output flow energy induces fine fuel atomization, and as a result a small SMD can be observed.

Higher injection pressure induces higher droplet velocity, and the faster droplets may lead to fine atomization. For this reason, the velocities of the detected fuel droplets in each flow region are represented in Fig. 14. As mentioned before, the approximately time dependent 50,000 droplets were averaged for more reliable measurement. As can be seen in this figure, many droplets having a mean velocity of around 9 m/s are detected in the turbulent flow region. As the flow region changes from turbulent to cavitating flow, most droplets have a mean velocity of around 10 m/s. Furthermore, the mean droplet velocity distributions move to over the 20 m/s for both *L*/*W* ratios in the hydraulic flip region.

Judging from above results, it can be said that the cavitation generated in the nozzle enhances the fuel atomization characteristics, and a longer nozzle orifice length induces more fuel droplet atomization.

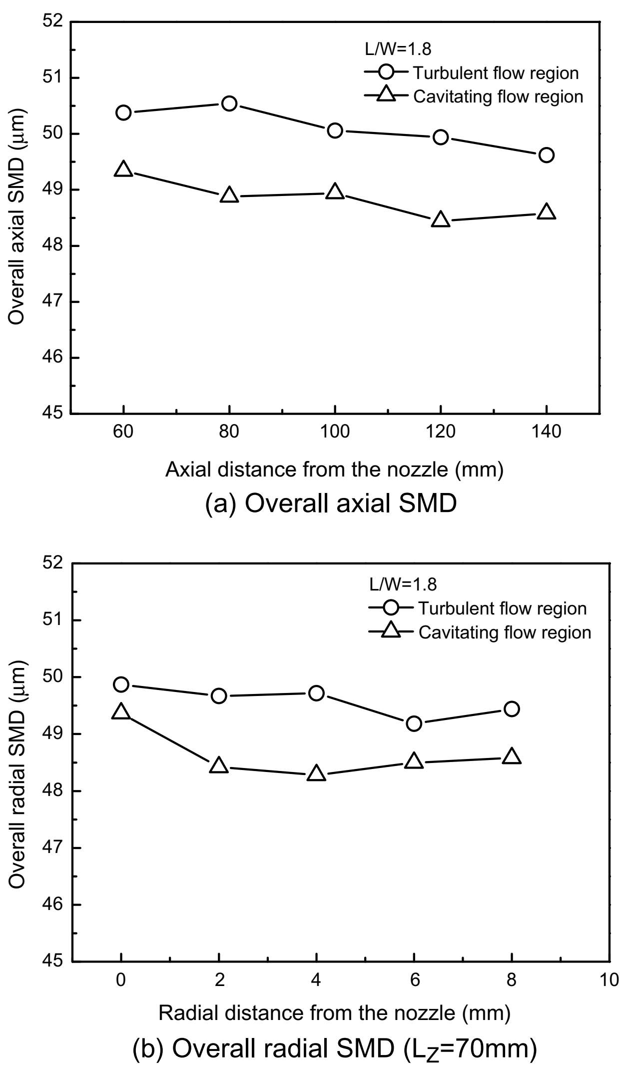

Fig. 12. Effect of flow characteristics on the overall SMD when $L/W = 1.8$.

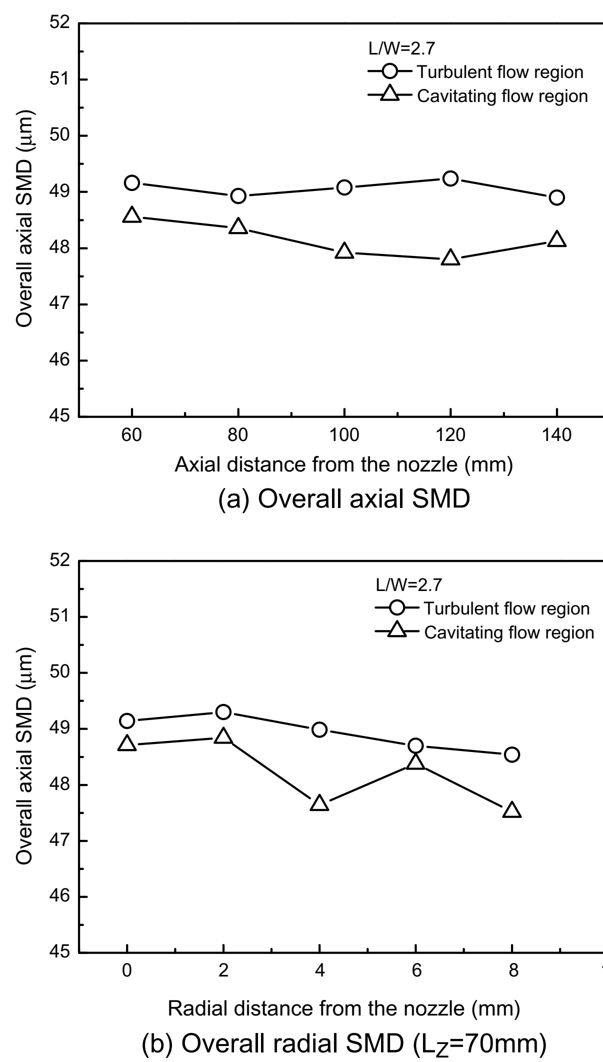

Fig. 13. Effect of flow characteristics on the overall SMD when $L/W = 2.7$.

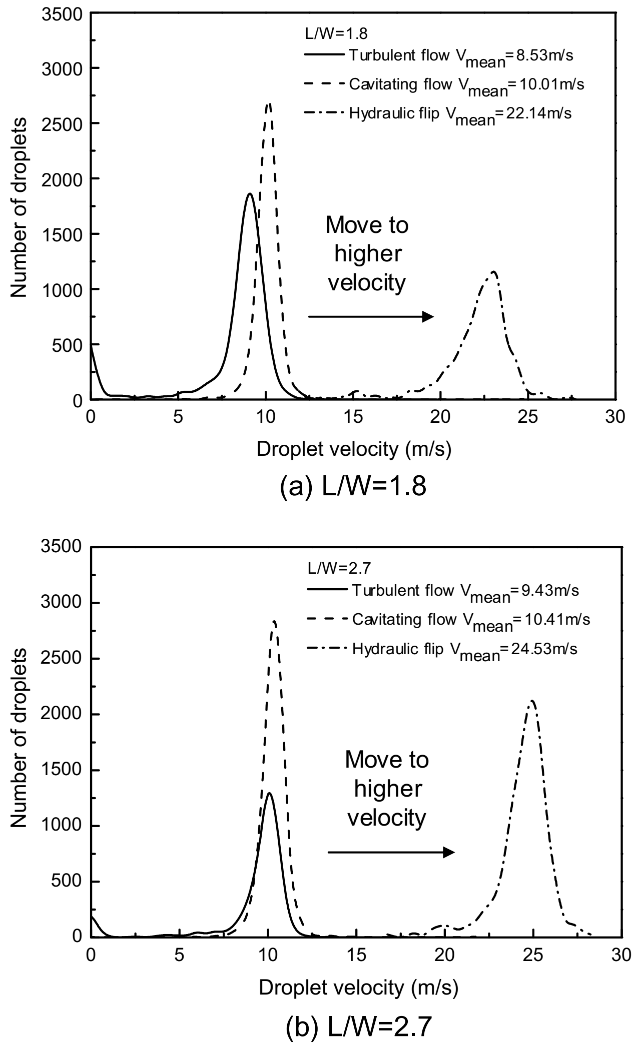

Fig. 14. Effect of flow characteristics on the detected droplet velocity.

4. Conclusions

In this study, the effect of nozzle cavitation on the spray atomization characteristics in nozzles with different length to width ratios was investigated in terms of overall droplet size, velocity, and counted percentage of detected droplets. The conclusions in this study are as follows:

1. The classification of cavitating flow can be divided into three regions, namely, turbulent flow region, cavitating flow region, and hydraulic flip region. In addition, cavitation creates a wider spray angle. In the long L/W ratio nozzle, the spray flow shape is not much wider because the axial flow movement to the downstream could be strong.
2. When L/W is 1.8, the cavitation can not be observed when the cavitation number is larger than 1.13 because it is turbulent flow. From 0.46 to 1.13 of cavitation number, cavitation is generated and developed along the nozzle orifice, and the flow characteristics change to the hydraulic flip characteristics in the range under the 0.46 of cavitation number. On the other hand, when L/W is 2.7, the cavitation occurs when the cavitation number is 1.61, increased in the range from 0.54 to 1.61 of cavitation number, and hydraulic flip occurs within the range of 0.54 of cavitation number.
3. In case of $L/W = 1.8$, the spray cone angle is larger than those of $L/W = 2.7$ in a whole injection pressure range. As the injection pressure increases, the flow changes from turbulent flow to cavitation flow, and the spray angle increases. It shows the maximum values, and the spray cone angle decreases dramatically due to the hydraulic flip characteristics. From these results, it can be said that the small L/W ratio induces the wider spray area, and it can lead to the fine droplet breakup process.
4. In case of $L/W = 1.8$, the discharge coefficient is higher than that of $L/W = 2.7$ because the liquid jet formed at a vena contracta has no time re-expand and fill the nozzle due to the short length. When $L/W = 2.7$, the jet expands in the nozzle and the discharge coefficient decreases due to the low flow rate. It can be assumed that further increase in L/W ratio will reduce the discharge coefficient due to increase of friction loss.
5. The SMD values for the axial and radial direction in the cavitating flow are smaller than that of turbulent flow. This indicates that the divergence of the bubble breakup energy formed by cavitation induces fine atomization and cavitation could be the dominant factor in enhancement of fuel atomization.
6. Many droplets having a mean velocity of 9 m/s are detected in the turbulent flow region. As the flow region changes to the cavitating flow, most droplets have a mean velocity of around 10 m/s. Furthermore, the mean droplet velocity distributions move to over the 20 m/s for both L/W ratios in the hydraulic flip region.

Acknowledgements

This study was supported by the CEFV (Center for Environmentally Friendly Vehicle) of the Eco-STAR project from MOE (Ministry of Environment, Republic of Korea). Also, this work is financially supported by the Ministry of Education and Human Resources Development (MOE), the Ministry of Commerce, Industry and Energy (MOCIE) and the Ministry of Labor (MOLAB) through the fostering project of the Lab of Excellency.

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