Study on Effect of Nozzle Hole Length to Diameter Ratio on Near-Field Diesel Spray Characteristics at High Density Conditions

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ABSTRACT: The diesel engine commonly introduces high boost pressure to achieve high engine efficiency. This extra air is supposed to significantly influence liquid vaporization. In experiment, surrounding gas conditions of 7 – 46.8 kg/m³ were prepared by rapid compression and expansion machine RCEM. The nozzle length hole to diameter ratio L/D ratio of 2.77, 3.73, 4.44 and 6.94 were used corresponding to orifice diameter of 0.072 – 0.180 mm. The close-up region from nozzle tip to 20 mm downstream was focused to simultaneously capture the vapor and liquid phases using shadowgraph and light scattering technique respectively. The information extracted from the images was then used for estimation of fuel mixture in the near-field spray incorporated with a simple 1D jet model. The result showed that liquid length was dominated by both gas density including gas temperature and rate of fuel injection. The vapor cone angle showed tendency to increase with L/D ratio decreased. The widest vapor cone angle was found at L/D ratio of 2.77 which corresponded to achievement of the highest mass of fuel in vapor phase. It was an evidence that atomization is also one of the essential factors to improve vaporization. At the same gas temperature of 890 K, the fuel mass in liquid phase considerably reduced with increasing gas density. An increase in gas density resulted in substantially increase in entrainment. With identical orifice diameter of 0.180 mm, the smaller L/D=2.77 reported better atomization, shorter liquid length and enhanced entrainment compared with L/D=4.44.

KEY WORDS: heat engine, compression ignition engine / near-field diesel spray, L/D ratio, high surrounding gas density, liquid length, RCEM [A1].

1. Introduction

The mixture formation plays a dominant role in diesel engine, because it relates with the combustion efficiency subsequently resulting in fuel consumption and emission. In direct injection diesel engine, the injected fuel is required to distribute properly and complete evaporation within a short time interval in combustion chamber for shortening the time to combustion. An understanding of a spray behavior is a standpoint as one of the most significant challenges for engine design. The current diesel engine employs high boost pressure, high injection pressure and high exhaust gas recirculation (EGR) rates to achieve better output power and meet emission standards. These strategies provide a typical top-dead center (TDC) gas condition before fuel injection exceeding 4 MPa and 800 K [1]. Under the conditions which the surrounding pressure and temperature exceeding the thermodynamic critical point of the injected fuel, fuel jet exhibits remarkable characteristics which are distinctive fashion compared with that at low pressure and temperature according to fundamental thermodynamic analysis [2, 3]. Because of the diminishment of surface tension and enthalpy of vaporization, the sharp distinction between the liquid and gas phases vanishes. The improved microscopic diagnostics [4] was conducted at the near-nozzle field region. They reported above certain pressures and temperatures a dense fluid mixing with diminishing surface tension was observed for n-dodecane sprays after the end of injection (EOI). Several spray visualization techniques have been available for a study of fuel spray physics such as X-ray [5-7], planar laser-induced exciplex fluorescence (PLIEF) [8], phase doppler interferometry (PDI) [9] and high-speed shadowgraph imaging [10]. To determine the liquid phase in the spray, Mie scattering is a preferable imaging technique to visualize the liquid portion in the fuel jet [11]. There have been few publications presenting flow characteristics from different nozzle hole lengths [12, 13]. The computational fluid dynamics (CFD) simulations for different nozzle configurations were performed and described the flow behaviors inside the nozzles [14]. From the literature reviewed in spray diagnostics, it has been limited research works conducted the simultaneously imaging for vapor and liquid phase fuel spray particularly focusing on near nozzle region. The objective of the present work is to investigate the effect of nozzle hole length to diameter ratio under wide ranges of surrounding gas condition. The experiment employs an optical microscopy technique to capture liquid and vapor phase information in near-field region.

2. Experimental Setup

In this study, it is intended to separately image both vapor and liquid phases of fuel spray in order to observe spray structure and vaporization characteristics of injected fuel when emerges into large variation of gas condition. The light scattering imaging
The scattering technique is properly selected as an indicator of liquid phase and high density spray. The scattering technique employed in this study was verified validity whether light scatters only from liquid or includes gas phase. The Rayleigh scattering [15] describes the scattering from the gas phase and molecules, while Mie scattering [16] accounts for scattering from liquid fuel droplets. In calculation, a simple one-dimensional jet model [17] was employed to estimate mixture fraction and number density of gas phase. The Rayleigh scattering cross section of diesel fuel was obtained from [15] and the approximated diesel droplet diameter of 20 µm was used for liquid phase. As a result, averaged intensity difference between Rayleigh and Mie scattering regimes showed as entirely different as in order of 14-15 for wide range of surrounding gas conditions of 4-6 MPa and 500-900 K for pressure and temperature respectively. Therefore, the large difference between those scattering regimes is fairly reasonable for the scattering imaging technique used for quantification of liquid portion inside spray. In classical shadowgraph, a shadowgraph of diesel sprays includes both shadows of liquid phase and of vapor phase fuel. The desired surrounding gas conditions conducted in this work were prepared by rapid compression-expansion machine (RCEM) [18]. The compression chamber and optical accessible arrangement are schematically shown in Fig. 1 and the layout of quartz window is shown in Fig. 2b. In this experiment, 0-20 mm from nozzle tip towards downstream spray was taken by means of simultaneous classical shadowgraph and scattering imaging technique. Specifications of imaging devices are listed in Table 1. The pulsed-diode laser (CAVILUX HF) with wave length of 640 nm was used as a light source for both scattering and shadowgraph. With this system, the collimated incident laser light with beam diameter of approximately 20 mm was directed through the quartz window placed in front of the compression chamber. The fuel spray was achieved between two prisms, which were homogenously built with a quartz window. The prisms were used for irradiating the spray and imaging of shadowgraph. Once the fuel jet left the nozzle, the liquid fuel core and droplets were immediately illuminated by the light beam. The light emerged from right to left side perpendicular to the camera view. The laser light was pretty strong to illuminate the liquid droplets. From that, the neutral-density filter (ND 2.0) corresponding to transmittance of 0.01 was stuck in front of the quart at the shadow side to reduce amount of laser light and made shadowgraph to be visible clearly. Both images were captured at the same time by one high-speed CMOS camera (MEMRECAM

**Table 1 Imaging condition.**

| Light source     | Pulsed-diode laser |
|------------------|-------------------|
| Wave length      | 640 nm            |
| Pulse duration   | 90 ns             |

**Table 2 Experimental conditions in RCEM.**

| RCEM and Chamber specifications |       |
|---------------------------------|-------|
| Piston speed                    | 30 ms/comp. (~1200 rpm) |
| Bore x Stroke                   | 30 x 150.5 mm |
| Displacement                    | 425.32 cc |
| Compression ratio               | 12.1 |

**Injection conditions**

| Nozzle hole number | 1 (all nozzles) |
|--------------------|-----------------|
| Orifice diameter D, Nozzle | 0.180 mm, 0.5 mm, (2.77) |
| hole length L, (L/D)     | 0.134 mm, 0.5 mm, (3.73) |
|                         | 0.180 mm, 0.8 mm, (4.44) |
|                         | 0.072 mm, 0.5 mm, (6.94) |
| Fuel temperature        | 310 K (± 10 K)  |
| Injection pressure       | 150 MPa         |
| Injection duration       | 1.5 ms          |
| Fuel properties          |                 |
| n-paraffins % mass       |                  |
| C_{15}H_{32} : 11.6%      |                  |
| C_{16}H_{34} : 62.6%      |                  |
| C_{17}H_{38} : 25.7%      |                  |
| Critical pressure        | 1.67 MPa         |
| Critical temperature     | 677 K            |
| Density at 300 K         | 745.3 kg/m^3     |
| Surface tension at 300 K | 20.8 mN/m        |

**Surrounding conditions**

| Gas     | Nitrogen |
|---------|----------|
| Pressure (P_g)     | 1.8 – 12.4 MPa |
| Temperature (T_g)  | 534 – 890 K    |
| Density (p_g)      | 7 – 46.8 kg/m^3|

*Fig. 1 Optical arrangement for simultaneously shadowgraph and scattering imaging.*

*Fig. 2 (a) Special designed quartz window with prisms and (b) Top-view layout in mm (not to scale).*
ACS-1) fitted with 105-mm-macro lens (f/2.8 Micro-NIKKOR). The captured area was 22 x 33 mm at 8.3 μs frame interval and the final optical resolution was 10 pixels/mm. An example of a taken photograph is also included in Fig. 1 showing the shadowgraph and scattering images on the left and right side respectively. During the experiment, the pulse duration remained constant which was set to be 90 ns for all operating gas conditions. One should be noted that the shadowgraph and scattering images were simultaneously taken using a high speed camera. With this, those photographs were taken at the view of 90-degree angle difference. In Table 2, the stroke of the RCEM was 150.5 mm with the compression ratio of 12.1. Four single-hole type nozzles with variation of L/D ratios were used for experiment. The injection pressure was kept at one pressure of 150 MPa and fuel inlet temperature was about 310 K. Due to small bore of 30 mm of compression chamber, injection duration was decided to be 1.5 ms to avoid impingement until imaging ended of injection state. Fuel properties consisted of three compositions with critical point of 1.67 MPa and 677 K for critical pressure and temperature respectively. The nitrogen gas was supplied as surrounding gas to suppress combustion.

3. Operating Gas Conditions

For the surrounding gas condition relevant to current diesel spray, gas pressure and temperature at top dead center TDC exceed 4 MPa and 800 K [1] respectively. Therefore, the experimental condition is determined to perform from surrounding gas conditions below the critical point of the used fuel through the supercritical region for wide range study of gas condition on spray structure and spray characteristics. In this experiment, the nitrogen gas was used as a surrounding gas. In Fig. 3, the operating gas conditions are plotted on the pressure versus temperature space with the critical point of the fuel included. The 17 conditions plotted are the total of prepared surrounding gas conditions at TDC before fuel injection. The gas pressure was measured by in-cylinder pressure sensor while the gas temperature took advantage of the adiabatic compression process. A wide range of surrounding circumstances is set ranging from 1.8-12.4 MPa and 534-890 K for gas pressure and temperature respectively. The gas conditions indicating in the P-T map are determined from the variation of study aspects which contains 3 classifications. The first one is three constant gas temperatures of 534 K, 712 K and 890 K. The second is three constant gas pressures of 1.86 MPa, 3.71 MPa and 7.44 MPa. The final is four constant gas densities of 11.7 kg/m³, 23.4 kg/m³, 35.2 kg/m³ and 46.8 kg/m³.

4. Results and Discussions

This section consists of five subsections. It begins with fuel injection rate at four different nozzle specifications. The second subsection shows the raw images obtained from the experiment with selected gas densities at gas temperature of 890 K. Then, the measured liquid length and measured cone angles are presented in the third and fourth subsection respectively. The last section is the estimation of mixture quantities based on measured data incorporated with one-dimensional jet model.

4.1. Rate of fuel injection

The rate of fuel injection is the rate of the fuel introduction into the combustion chamber. It is the consequence to spray evolution, fuel atomization and mixing with surrounding gas which are used to determine the combustion development. Therefore, it is important to understand injection behavior for each nozzle before pursuing the spray experiment. In this study, the injection rate measurement was based on the method proposed by Zuech [19, 20], according to which the injection is actuated in a closed, fixed-volume chamber filled with the same injected fluid. The single-hole type solenoid injectors of four varying nozzle hole length to diameter ratio L/D were used for the test. In the measuring chamber, the injection pressure was also kept at constant of 150 MPa. Fig. 4 shows measured injection rate profile which was activated by 2.2-ms injection signal. Additionally, the discharge coefficient C_d calculated from rate of fuel injection for each nozzle is provided. Injection profile with almost rectangular shape is observed. The initial rise of injection rate for all nozzle specifications is about 0.4 ms and injection almost ends at 3.3 ms from the start of injection. The different nozzle specifications clearly show the different averaged rate of fuel injection. It is carefully noted that the rate of fuel injection is not ranged in order, for example D=0.180 mm (L/D=4.44) achieves both the highest averaged rate of fuel injection of 10.8 mg/ms and the highest discharge coefficient of 0.85. However, the nozzle is not the largest L/D ratio. In Fig. 4,

![Fig. 3 P-T diagram representing surrounding gas conditions including critical point of the fuel. The dashed lines indicate constant gas density and constant gas pressure conditions.](image)

![Fig. 4 Comparison of measured rate of fuel injection using Zuech’s method. The legend presents four nozzle specifications used for injection test.](image)
the result of fuel injection rate test can be divided into three groups which is high rate of fuel injection for D=0.180 mm (L/D=4.44) and D=0.180 mm (L/D=2.77) while middle rate of fuel injection is D=0.134 mm (L/D=3.73). The lowest rate of fuel injection is found to be D=0.072 mm (L/D=6.94). It is noted that the nozzle L/D ratio of 2.77 and 4.44 come with identical orifice diameter of 0.180 mm. Comparing between D=0.180 mm (L/D=4.44) and D=0.180 mm (L/D=2.77) which are identical nozzle orifice size, the longer nozzle hole length provides the higher rate of fuel injection. It suggests that if the same fuel properties and same injection pressure are considered, the nozzle that comes with longer nozzle hole length would supply higher amount of fuel.

4.2. Near-field fuel spray visualization

The microscopic imaging was arranged to simultaneously perform the high-speed shadowgraph and scattering focusing on near-field region. From the setup, the 20-mm spray far from nozzle tip was appropriately captured with two types of spray information contained in a single shot of imaging. The shadowgraphy was used to represent the vapor phase spray boundary which includes fuel vapor and entrained gas. The scattering image corresponded to the liquid phase because of high density portion in the spray that dense enough to sufficiently light scattered. In Fig. 5, the fuel injects in the vertical direction from top to bottom. However, there was a possible case that a slightly inclined spray image was observed due to mounting issue. In image processing, spatial noise from variation of turbulence of surrounding gas is reduced from raw image by subtraction the previous image. To identify spray boundaries, a shadowgraph spray boundary is detected at sharp intensity gradient changed between spray and surrounding. For scattering image, 95-100% of maximum scattering intensity is used as a threshold to eliminate gaseous phase while retaining the relatively dense liquid region. A cone angle comprises of two lines marking from the nozzle outlet passing through the averaged values of the detected spray boundary fluctuations. For shadowgraph cone angle $\theta_{\text{st}}$, detection length is confined to be 12 mm for all gas conditions due to the limitation of visualization width that vapor phase is able to spread exceedingly. This is to ensure that all parts of vapor phase spray is strictly located inside the specified detection region. For liquid length LL, there were several cases that the liquid phase penetrated over the visualization region of 20 mm. However, if it exists inside the visualization region, the liquid length is measured to be 9.7 mm as shown in Fig. 5 on scattering image.

Fig. 6 displays instantaneous photographs directly captured from the experiment at gas temperature of 890 K. The images are tabulated vertically for different nozzle hole length to diameter ratio L/D of 2.77, 3.73, 4.44 and 6.94 from left to right respectively. The rows are arranged for different gas density of 46.8 kg/m$^3$, 23.4 kg/m$^3$ and 11.7 kg/m$^3$ from top to bottom respectively. The liquid length LL can be measured from the scattering image. However, not all gas conditions could be done, due to limitation of capturing length of 20 mm. In the scattering image, variation of light intensity is observed and it is essentially stronger at the spray centerline region. There are some variations of liquid phase cone angle incorporated with scattering intensity among gas conditions and nozzle specifications. The shortest liquid length is detected at D=0.072 mm (L/D=6.94) at gas density of 46.8 kg/m$^3$. This is as expected because this nozzle specifications provides the lowest rate of fuel injection in Fig. 4 resulting in the lowest spray momentum even more when interacts with surrounding gas. In addition, the small orifice diameter tends to promote breakup process leading to smaller droplet size. Both influences could contribute to improved liquid vaporization. Increasing the orifice diameter results in slowdown liquid vaporization as reported in D=0.180 mm (L/D=2.77), D=0.134 mm (L/D=3.73) and D=0.180 mm (L/D=4.44) at gas density of 46.8 kg/m$^3$. The shorter liquid length and wider scattering cone angle are observed at D=0.180 mm (L/D=2.77) compared with those of D=0.180 mm (L/D=4.44), both are identical orifice diameter. It can be thought that the longer liquid length of D=0.180 mm (L/D=4.44) is reasonable due to higher rate of fuel injection tends to lack of fuel-ambient heating process. In this pair, D=0.180 mm (L/D=2.77) is found to achieve better atomization process due to wider scattering cone angle. An improvement in atomization process is found to promote mixing process as it can obviously seen the shorter liquid length compared with D=0.180 mm (L/D=4.44). For low gas density of 11.7 kg/m$^3$, the D=0.180 mm (L/D=2.77) is found to be the largest liquid portion. The influence is comparable manner as shown in high gas density which D=0.180 mm (L/D=2.77) always reports the widest liquid cone angle. For overall observation of scattering image, as the gas density decreases with keeping gas temperature constant, this noticeably slows down liquid vaporization process. It is noted that the results of liquid cone angle and liquid length could not sequentially arranged in order regarding the L/D ratio. As the shadowgraph is sensitively detected the gas phase which includes liquid phase. The detected spray cone angles are useful for further analysis for estimation of fuel mixture. It can generally be seen that the vapor cone angle detected from shadowgraph image are wider than that of scattering for all image pairs. For D=0.180 mm (L/D=2.77), all gas densities gives the widest vapor cone angle.
The liquid length is measurement of the maximum axial penetration distance of liquid phase fuel existing in an evaporating spray [21, 22]. To obtained information such as cone angle and liquid length from the taken images, image processing is carefully performed to appropriately detect liquid region as described at early stage in section 4.2. It is noted that not all experimental conditions that the liquid length can be detected. For example at high gas temperature but low gas density, the liquid is possible to penetrate over the capturing area of LL=20 mm far from nozzle tip. Therefore, the liquid length can not be detected from those conditions. However, this issue of over visualization length is considered as 20 mm and used in section 4.5 for estimation of fuel mixture. Fig. 7 shows the effect of gas density on liquid length for four different nozzle specifications at gas temperature of 712 K and 890 K. From observation, the smallest orifice diameter of D=0.072 mm (L/D=6.94) provided the lowest rate of fuel injection exhibits the shortest liquid length. For D=0.072 mm (L/D=6.94) at the highest gas density of 46.8 kg/m$^3$, the liquid length of 5.02 mm and 7.84 mm are measured on gas temperature of 890 K and 712 K respectively. At gas density of 46.8 kg/m$^3$ for both gas temperatures of 890 K and 712 K, the longest liquid length is detected at D=0.180 mm (L/D=4.44), which nozzle gives the highest rate of fuel injection. Its value is reported to be 15.02 mm and 19.42 mm for gas temperature of 890 K and 712 K respectively. The liquid length measured at gas temperature of 890 K shows about 2.7 mm shorter than that of 712 K. This is a characteristics that the gas temperature is one of the main factors affecting the liquid length. The liquid length clearly shows an increasing tendency with decreasing surrounding density. It is found that an increase in L/D ratio is not responsible for shortening liquid length. The liquid length shows more sensitive to the rate of fuel injection and surrounding gas condition without relation with L/D ratio.

### 4.4. Effect of gas density on spray cone angles

The shadowgraph and scattering images were digitalized to obtain vapor and liquid phase boundaries respectively. Fig. 8a-8c present the measured liquid cone angle. The figure is vertically arranged for different gas temperature for 534 K, 712 K and 890 K ranging from the top to bottom. The liquid cone angle is plotted versus gas density for different four nozzle specifications. Each figure includes the legend to give detailed specifications of the nozzle and the marker information. It is generally seen that the liquid cone angle almost remains unchanged at high gas temperature of 890 K even when the gas density is changed. In Fig. 8b at gas temperature of 712 K, the liquid cone angle detected from D=0.180 mm (L/D=2.77), D=0.134 mm (L/D=3.73) and D=0.072 mm (L/D=6.94) increase slightly with increasing gas density except D=0.072 mm (L/D=6.94). Fig. 8a is at gas temperature of 534 K, it is classified as the lowest gas temperature of 534 K shows about 2
temperature in this experiment. It obviously exhibits that the liquid cone angle detected from D=0.180 mm (L/D=2.77) and D=0.134 mm (L/D=3.73) gives a tendency to increase with increasing gas density. The variations of liquid cone angle with gas density at low gas temperature is likely to be happened when spray dispersion is governed by breakup process. However, at high gas temperature, large difference between surrounding and liquid temperature can result in improvement in droplet heating and evaporation processes. This influence potentially overcomes dispersion of droplet associated with atomization. That is one possible reason caused liquid cone angle remaining unchange with increasing gas density for gas temperature of 890 K. Fig. 9a-c displays measured vapor cone angle which is observed from shadowgraph. For overall observation, cone angle considerably increases with increasing the gas density, and it becomes more sensitive at higher gas temperature. This is implied that vapor cone angle is dominated by vaporization process due to high variation of cone angle actively found at high temperature range. This spreading angle increasing tendency is unlikely the same as liquid atomization which is high tendency to take place at low gas temperature. Comparing among nozzle specifications for each gas temperature provides and global conclusion that the D=0.180 mm (L/D=2.77) overcomes the others indicated the highest dispersion. An increase in gas temperature with the same gas density show liquid vaporization favored resulting into wider vapor cone angle and shorten liquid length shown in Fig. 7. The smallest cone angle is indicated to be the nozzle D=0.072 mm (L/D=6.94 mm). This is because the small orifice diameter comes with low spray momentum and lack of spray concentration due to low rate of fuel injection that cannot achieve appropriate spray dispersion.

4.5. Fuel mixture characteristics in near-field region

In diesel combustion, the mixture preparation of fuel and surrounding gas is of primary importance to control combustion and emissions. For direct-injection engine, an atomized liquid spray evolves into a vaporized fuel jet as it penetrates into the
The mixing process is influenced by the density of surrounding gas. The non-entrained mass of liquid fuel is estimated at 7 kg/m³. It is noted that if the liquid fuel penetrates over 20 mm of visualization region, the liquid length is set to be 20 mm in calculation. The liquid fuel mass is obtained from the liquid density ρₙ₂ and fuel volume fraction X_{f} integrated over the liquid scattering region as expressed in Eq. (1). The calculation of vapor fuel mass is carried out in the region that liquid scattering region is subtracted from the vapor shadowgraph region as expressed in Eq. (2). In Eq. (3), the entrained gas mass is calculated in whole spray zone including liquid scattering zone. The calculation needs surrounding gas density ρₙ₂ and entrained gas volume fraction 1 − X_{f}. In experiment, the fuel vapor phase continuously penetrated through the capture area which is over 20 mm measured from nozzle tip. It should be noted that the integration in streamwise direction dz for vapor fuel and entrained gas are restrictively considered with VL=20 mm.

Fig. 11 presents effect of gas density on mass of liquid fuel for four different nozzle specifications at gas temperature of 890 K. In horizontal axis, the surrounding gas density ranges between 7-46.8 kg/m³. It is globally seen that increasing the gas density stimulates liquid phase to be vaporized into gaseous phase as a decrease in liquid mass for all nozzle specifications. At all gas densities, the D=0.072 mm (L/D=6.94), shows substantially lower amount in liquid fuel mass compared with that of the others due to the lowest rate of fuel injection. It obviously coincides with small fuel scattering region shown in Fig. 6 compared to the other nozzle specifications at the same gas density. The D=0.134 mm (L/D=3.73) shows significant reduction of liquid fuel mass in the range of gas density of 7-23.4 kg/m³ and then keeping slowdown reduction until 46.8 kg/m³. This could suggest that the mixing process is efficiently performed at low to moderate gas density. Due to large nozzle orifice size of D=0.180 mm (L/D=2.77) and D=0.180 mm (L/D=4.44), the result shows high liquid fuel mass in all levels of gas density excepting at gas density of 7 kg/m³ reporting somewhat.

The entrained gas amount m_{n2} is as follows

\[ m_{n2} = \int_{0}^{VL} \int_{0}^{2\pi} \int_{0}^{r_{sha}} \rho_{f,eq} \bar{X}_{f}(r,z) r dr d\theta dz \]

where \( \rho_{f} \) and \( \rho_{n2} \) are the fuel and surrounding densities respectively. The \( r_{sha} \) and \( r_{sct} \) are the radius of spray in scattering image and in shadowgraph respectively. The LL is the liquid length and VL is the visualization region. It is noted that if the liquid fuel penetrates over 20 mm of visualization region, the liquid length is set to be 20 mm in calculation. The liquid fuel mass is obtained from the liquid density \( \rho_{f,eq} \) and fuel volume fraction \( \bar{X}_{f} \) integrated over the liquid scattering region as expressed in Eq. (1). The calculation of vapor fuel mass is carried out in the region that liquid scattering region is subtracted from the vapor shadowgraph region as expressed in Eq. (2). In Eq. (3), the entrained gas mass is calculated in whole spray zone including liquid scattering zone. The calculation needs surrounding gas density \( \rho_{n2} \) and entrained gas volume fraction \( 1 - \bar{X}_{f} \). In experiment, the fuel in vapor phase continuously penetrated through the capture area which is over 20 mm measured from nozzle tip. It should be noted that the integration in streamwise direction \( dz \) for vapor fuel and entrained gas are restrictively considered with VL=20 mm.

Fig. 10 Quantification of mixture fraction based on diesel jet with momentum flux transport developed by Musculus [17]. The liquid length LL, visualization region VL, scattering \( \theta_{sct} \) and shadowgraph \( \theta_{sha} \) cone angles are specified.
lower amount of liquid fuel for D=0.180 mm (L/D=4.44). In the condition that the gas density higher than 20 kg/m$^3$, the liquid mass resulted from the D=0.180 mm (L/D=2.77) shows lower liquid fuel mass compared with that produced from D=0.180 mm (L/D=4.44). This result is a consequence of previous section of comparable liquid cone angles together with large vapor cone angle expanded by efficiently mixing process with stimulating a liquid vaporization. As a result, whole spray mixture fraction for D=0.180 mm (L/D=2.77) becomes diluted. However, the low amount of liquid fuel is observed for D=0.180 mm (L/D=4.44) for gas density of 11.7 kg/m$^3$. The result of liquid fuel mass is consistent with cone angles of both scattering and shadowgraph reported in Fig. 8 and Fig. 9 showing small cone angles. It would be the reason that high momentum jet with low aerodynamic drag of back pressure resulting into dense spray phase with lack of atomization process that the mixture could not be developed within this visualization region of 20 mm. Comparing between the D=0.180 mm (L/D=2.77) and D=0.180 mm (L/D=4.44) which are identical orifice diameter of 0.180 mm, the shorter nozzle hole length of L/D=2.77 is found to achieve better vaporization in moderate and high gas density.

The different nozzle orifice sizes would of course provide the different rate of fuel injection as well as the difference in spray formation characteristics. In addition to mass of liquid fuel, the fuel vapor phase produced which is a consequence of liquid break up and improved mixing due to entrained gas is shown in Fig. 12. It is quantification of amount of vapor phase fuel with compensation of different rate of fuel injection due to orifice size different. The vertical axis is the mass ratio of vapor fuel m$_{vfp}$ over the total fuel which is m$_{flq}$ + m$_{vfp}$. This is as expected from the result depicted in Fig. 11 that decreasing in liquid mass would be a consequence of an increase in vapor mass. The global tendency for all nozzle specifications shows the fuel vapor mass produced with increasing gas density, indicated almost the ratio of 0.9 at gas density of 46.8 kg/m$^3$ for all nozzle specifications except D=0.180 mm (L/D=4.44). With the smallest nozzle orifice size D=0.072 mm (L/D=6.94), the mixture is improved quickly as increasing the gas density and reaches its highest level at gas density of 30-46.8 kg/m$^3$. The injection from a small orifice size is that the fined droplets are forming a possibility for achieving liquid vaporization process. For D=0.134 mm (L/D=3.73), the ratio of vapor fuel mass drastically increases from 0.22 to 0.82 at gas density ranging from 7 to 23.4 kg/m$^3$ and then remains a slight increase. For the identical orifice size of 0.180 mm, both nozzles show similar characteristics of almost linearly produced fuel vapor. However, the nozzle orifice size D=0.180 mm (L/D=2.77) exhibits favorable mixture compared with that D=0.180 mm (L/D=4.44). This higher fuel vapor mass at middle to high gas density range for D=0.180 mm (L/D=2.77) is a relevant outcome from reduction of fuel liquid mass shown in Fig. 11.

In diesel spray, air entrainment plays an important role in mixing process related with heating and evaporation of liquid fuel. It is a key factor which affects the spray formation, local equivalent ratio and ignition process for combustion view point. In this study, air entrainment was calculated based on a fuel mixture fraction considering from full spreading angle as schematically expressed in Fig 10. Fig. 13 shows mass of entrained gas characteristics for different nozzle specifications with increasing gas density. Increasing the gas density directly stimulates the atomization process resulting in wider spray cone angle. With those points, it gives a chance for entrainment of surrounding gas into the spray. All nozzle specifications show significantly improvement in air entrainment with increasing gas density. With the smallest orifice size nozzle D=0.072 mm (L/D=6.94), it shows the lowest mass of entrained gas for all gas density range compared with the other nozzles. This is because the low rate of fuel injection that could not provide enough spray momentum to interact with surrounding gas leading to

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**Fig. 12** Effect of gas density on fuel vapor mass to total fuel mass ratio for $T_g = 890 \text{ K}$.  
**Fig. 13** Effect of gas density on entrained gas mass for $T_g = 890 \text{ K}$.  
**Fig. 14** Effect of gas density on fuel vapor to entrained gas mass ratio for $T_g = 890 \text{ K}$.  

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slowdown spray development. The smaller vapor cone angle is observed for this smallest nozzle specification. With orifice size nozzles of 0.180 mm, the shorter hole length D=0.180 mm (L/D=2.77) provides higher mass of entrained gas, which is found to be a unique feature for this shorter hole length nozzle. Due to high rate of fuel injection for D=0.180 mm, as previously discussed in produced fuel vapor mass, Fig. 13 for nozzle D=0.180 mm nozzle provides an evidence to support that the higher amount of entrainment help improvement in liquid vaporization process. Fig. 14 presents the effect of gas density on fuel vapor mass to entrained gas mass ratio. The value of \( m_{np}/m_{ng} \) ratio provides information about how large amount of gas entrained into the spray compared with fuel vapor phase. The mass ratio exhibits lower than unity for all nozzle specifications except gas density of 7 kg/m\(^3\) for D=0.072 mm (L/D=6.94). In previous discussion of Fig. 12 and Fig. 13, it was found that both vapor fuel mass and entrained gas mass increase with increasing gas density. In addition to those descriptions, Fig. 14 indicates that the entrained gas even more increases with increasing the gas density since the large amount of entrained gas compared with amount of fuel vapor made the mass ratio considerably declined versus gas densities for all nozzle specifications. The vapor fuel to entrained gas mass ratio generated by each nozzle specifications roughly reports comparable values for all surrounding gas density except gas density of 11.7 kg/m\(^3\). It should be noted that, the nozzle D=0.180 mm (L/D=2.77) exhibits a similar level of vapor-gas mass ratio at gas density of 25-46.8 kg/m\(^3\) compared with that D=0.180 mm (L/D=4.44). This is not because of lack of produced fuel vapor but due to higher amount of entrainment. The present procedure given so far is the estimated spray mixture quantities obtained from taken liquid and vapor fuel phase photographs, which would be useful for further study on fuel-spray ignition and combustion characteristics.

5. Conclusions

The effect of nozzle hole length to diameter ratio was investigated using a rapid compression-expansion machine under wide range of operating surrounding gas conditions. High-speed microscopy experiment was performed to capture vapor and liquid phase in diesel fuel spray at near-field region. The information extracted from the images was then used for estimation of fuel mixture. The main results of this work are listed below:

1. Liquid length was dominated by both gas density including gas temperature and injected fuel amount. It was not absolutely only contributed by L/D ratio. Liquid cone angle noticeably increased with increasing gas density at low gas temperature of 534 K. It was relatively unchanged at gas temperature of 712 K and 890 K since dispersion could possibly be suspended at higher gas temperature. Vapor cone angle was observed to increase with L/D ratio decreased. The widest vapor cone angle was found at D=0.180 mm (L/D=2.77) corresponded to achievement of the highest mass of fuel in vapor phase.

2. At constant gas temperature of 890 K, fuel mass in liquid phase considerably decreased with increasing gas density. Hence, atomization was stimulated by increasing gas density, then consequentially to promote liquid vaporization. However, the vaporization became weaker at elevated gas density for small orifice size nozzles D=0.134 mm (L/D=3.73) and D=0.072 mm (L/D=6.94) due to low rate of fuel injection.

3. An increase in gas density showed substantially produced vapor fuel. Until a certain gas density, the vapor phase became moderate fashion with increasing gas density for the orifice diameters smaller than 0.180 mm. For orifice diameter of 0.180 mm on both L/D=2.77 and L/D=4.44, the vapor fuel mass almost linearly increased with increasing gas density.

4. For fuel vapor to entrained gas mass ratio at high density range of 30-46.8 kg/m\(^3\), it was found to be comparable for identical nozzles D=0.180 mm due to higher amount of both fuel vapor and entrained gas produced by D=0.180 mm (L/D=2.77) and lower amount of both quantities by D=0.180 mm (L/D=4.44).

5. With identical orifice diameter of 0.180 mm, the smaller L/D=2.77 which corresponds to shorten nozzle hole length achieved mixing process, shorten liquid length and superior entrainment compared with L/D=4.44.

6. With large variation of nozzle orifice size of the present study, to describe the effect of gas condition on liquid and vapor phase quantities in spray, not either L/D ratio or orifice diameter, both are necessary information. This is because the orifice diameter affects rate of fuel injection.

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