Near-Nozzle Dynamics of Diesel Spray under Varied Needle Lifts and Its Prediction Using Analytical Model

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Due to the lack of sufficient measurement methods, great difficulties are still present in clarifying the relationship between the nozzle internal flow and liquid-jet dynamics, especially when considering the needle motion effect. In this study, by utilizing the x-ray phase-contrast imaging (XPCI) technique, the in-nozzle needle motion characteristics and the liquid-jet dynamics in the near-nozzle field have been measured within a wide range of injection-pulse durations, based on which the needle-lift dependence of liquid-jet dynamics has been discussed in detail. The study is important for the nozzle related investigations, especially in view of the increasingly widely adopted multiple-injection strategies in the injection systems. The results indicate that, ruled by the mass flow equilibrium inside the nozzle sac, the liquid-jet flow dynamics in the near-nozzle field is closely related to the needle lift and injection pressure. Insufficient needle lift under short injection-pulse duration hurts the liquid-jet momentum that should be highly considered in the multiple-injection strategies. An analytical model has also been proposed to predict the jet axial velocity in the near-nozzle field. The model was found to have good agreement with the experimental results at different conditions.

KEY WORDS: *diesel injector, injection pulse duration, needle lift, jet axial velocity, analytical model.*

1. Introduction

The precise control of injection event contributes greatly to the optimization of engine performances and the reduction in pollutant emissions. In the last few decades, substantial efforts have been made to unveil the fundamental nature of fuel sprays and associated phenomena, such as spray behaviors under different injection pressures [1-2], different environment conditions [3-4], and different fuel properties [5-6]. These investigations proved that the high-speed relative motion between the liquid jet and environment gas is one of the key factors causing the jet disintegration and atomization. Nevertheless, because of the highly transient and multiphase process of fuel injection, the inherent mechanism of spray atomization and evaporation has not been conclusively determined [7-8] yet.

Lately, increasing attentions have been drawn to the flow characteristics inside the diesel nozzle due to its profound influence on the near-field spray behaviors. The investigations showed that the in-nozzle flow is strongly affected by the nozzle internal geometrical factors and the needle motion. From one aspect,

the influence of the nozzle geometry on the internal flow [9-10], spray macroscopic structure [11-14] and mass flow rate [15-16] have been widely discussed. Many solid conclusions have been gained and thereby some numerical models have also been established [17-18]. For instance, by utilizing a recently developed primary breakup model (KH-ACT), Som et al. conducted the simulation study to reveal the effect of the orifice structures on the in-nozzle flow, spray, and combustion process [18]. Different from the previous studies, in Som et al.'s simulation the effects of cavitation and turbulence inside the diesel nozzle were coupled with the effect of aero dynamics to decide the spray breakup and atomization processes. Their results showed that the conicity and hydro-grinding reduce the cavitation and turbulence inside the nozzle, and then slow down primary breakup, increase spray penetration, reduce the vaporization rate and fuel air mixing, and ultimately cause the ignition occurring further downstream.

From another aspect, the needle motion inside diesel nozzle has also been proved to play a decisive role for the spray dynamics [19-21]. However, by utilizing the conventional measuring methods, the needle lift is either calculated from other indirectly measuring parameters, or measured with the displacement sensor that is mounted centimeters away from the needle tip on the injector body. These measurements unavoidably bare the defects of insufficient accuracy. While experimental researches were exposed to great difficulties, the numerical investigation has become another important method [21-23]. For instance, Margot et al. [21] conducted the simulation investigation with the three dimensional moving-mesh method. Their results showed that the turbulence kinetic energy of internal flow is mostly created by the needle motion. At the low needle lifts, during opening and closing, the turbulence kinetic energy is more intense compared to that at the high needle lifts.

In recent years, a promising technique based on x-ray phase-contrast imaging (XPCI) was employed to analyze the diesel spray. The high-energy and short-pulse (sub-ns to 10's ns) x-ray beam enables the direct imaging of the needle motion through the steel nozzle tip and high-speed jet in the near field without severe scattering and absorption. Based on this technique, several investigations have been conducted to analyze the needle motion under the actual operating conditions [24-25], near-nozzle jet dynamics [26-27], and structures of diesel jets [28-29]. However, a thorough investigation to understand the needle-lift dependence of near-nozzle liquid-jet dynamics is still missing especially in the wide-range injection-pulse durations. This study is actually very important accounting for the increasingly widely adopted multi-injection strategies in injection systems. Within the multi-injection strategies, the conventional main injection event is split into two or more shorter pilot-injection events, which can effectively improve engine performance compared to the single-injection strategy [30-31]. Nevertheless, further shorten the pilot-injection event may cause the needle lift apparently lower than its normal situation, which on the contrary potentially results in

the injection being unstable, decreasing the liquid-jet velocity, slowing the breakups, and then further humbling the combustion. Therefore, it is highly significant to define the correlation between the needle motion and the jet dynamics, especially at the short injection-pulse durations.

In this study, by taking advantage of the XPCI technique, we firstly measured the in-nozzle needle motion and the near-field liquid-jet dynamics, including the jet axial velocity and lateral width, within a wide range of injection-pulse durations. Then the needle-lift dependence of near-field jet dynamics was discussed in detail. The critical needle-lift to ensure the sufficient jet momentum was defined. Furthermore, an analytical model was proposed to predict the near-field jet axial velocity, which will not only greatly promote the understanding of the correlation between the needle lift and the jet dynamics, but also benefit for pilot-injection control in the multi-injection strategies.

2. Description of experiments

2.1 Experimental setup

We used the similar experimental setup for XPCI that was described in previous investigations [26-27]. Fig. 1a shows the sketch of XPCI setup at 7ID and 32ID beamlines of the Advanced Photon Source (APS), a third generation synchrotron x-ray source. In the Hybrid-Singlet beam mode of APS, an irregular pulse pattern is generated for each cycle with 3.682 μ s period as presented in Fig. 1a and 1b. This pulse pattern contains a single-bunch with a 150ps duration and a 16 mA current isolated from the remaining 8 group of 7 consecutive bunches (8 septets) with 11 mA current per group and a periodicity of 68 ns. The x-ray pulses needed for each analysis item can be received for imaging by proper phase and time control of the camera exposure. For specific, the x-ray timing pattern A includes eight septets with a total electron current of 88 mA and a length of 472 ns (part A in Fig. 1b). This pulse train has sufficient high-energy x-ray photons, which can be used for visualizing the in-nozzle needle motion through the steel nozzle enclosure. The total pulse duration of 472 ns was short enough to freeze the needle motion during the injection process, which have the speed of around a meter per second.

The near-nozzle field liquid-jet structures were visualized using the x-ray timing pattern B with an electron current of 16-mA and a length of 150-ps (part B in Fig. 1b). This pulse provides an extremely high time resolution for imaging, which makes it possible to capture the liquid-jet structure in the near-nozzle field that is so dense and turbulent to access by the conventional optical methods. The liquid-jet velocity was derived using the 2 septets with 11-mA current, 17-ns width, and 68 ns period (part C in Fig. 1b). Compared to other light sources, the synchrotron x-ray source contains the pulses with a

101 very short time interval, suitable to capture the double exposed x-ray images for velocity measurements.

102

103

104 **FIG. 1.** Experiment setup for x-ray phase-contrast imaging (a) and x-ray pulse timing pattern used for
 105 PCI-based single-pulse or multi-exposure experiments (b).
 106

107 2.2 Data analysis

108 Fig. 2a-b show the measurement method of the needle motion. Once the time-sequential images of
 109 needle motion are obtained, the needle lift profile can be calculated by cross-correlation of the needle
 110 images at the original location and measuring location. In this study, the jet axial velocity was introduced
 111 to describe the jet dynamics in the near-nozzle field due to its profound influence on jet evolution and
 112 atomization. To obtain the jet axial velocity, an auto-correlation analysis is performed in a particular region
 113 of interest (ROI) of the double-exposure images, as shown in Fig. 2d-e. In this study, a square region is
 114 introduced as ROI, which was 1 mm away from the nozzle tip. Based on data of a previous study (Ref. 27),

the jet velocity decays to axial and radial direction as penetrating downstream. Different locations of region of interest may slightly affect the calculating results indeed. However, the focus of this study is the needle motion effect on the near-field jet dynamics and as the first step only the orifice exit velocity was considered. The displacement vector of the imaged features during the 68 ns time interval can be obtained by detecting the relative location of the displacement peak with respect to the center self-correlation peak. The detailed measurement method of the local spray velocity can be found in the recent publication [27].

FIG. 2. Illustration of the x-ray imaging data analysis method: (a-b) different-timing images to calculate the needle position using cross-correlation functions; (c) single-exposure spray image to calculate the liquid-jet expansion angle; (d-e) double-exposure spray image to calculate the liquid-jet velocity using 2D auto-correlation functions.

Besides the jet axial velocity (U_{axial}), liquid-jet expansion angle (θ) was also considered in the analysis of jet dynamics in the near-nozzle field. The θ is defined as the top angle of the trapezoid formed by the orifice outlet diameter and the liquid-jet width at 1 mm from nozzle exit, as seen in Fig. 2c. A larger θ will promote jet breakup and spray-air interaction.

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133 2.3 Experimental conditions

134 A commercial piezo injector with single-hole nozzle was used for the investigation. The injection
 135 pressures of 100 MPa and 200 MPa were selected. For each tested injection pressure, the environment gas
 136 density and temperature in spray chamber were fixed to atmospheric and room condition. Detailed
 137 information of the nozzle internal geometrical factors and injection conditions can be seen in the Table 1
 138 and Table 2, respectively. As mentioned in the introduction, the purpose of this investigation is to analyze
 139 the needle-lift dependence of near-nozzle liquid-jet dynamics. To realize that, flexible settings of
 140 injection-pulse duration were adopted. At short injection-pulse durations (0.02 ms - 0.30 ms), a fine time
 141 step of 0.02 ms was set to detect the critical needle-lift ensuring the high-speed jet. At long injection-pulse
 142 durations (0.30 ms - 1.00 ms), a rough time step was set to create more needle-lift displacement for better
 143 investigation.

144 **Table 1**
 145 Geometrical factors of test nozzle

Hole type	Inlet Diameter (μm)	Outlet Diameter (μm)	L (μm)	k-factor
Single-hole	154	124	800	3

146 **Table 2**
 147 Test condition matrix

Injection (MPa)	Ambient gas pressure (MPa)	Ambient gas temperature (K)	Ambient gas density (kg/m^3)	Fuel	Injection pulse (ms)	
					Short-pulse period	Long-pulse period
100, 200	Atmospheric (0.1)	Room condition (302)	1.25 kg/m^3 (N_2)	Diesel (US No. 2)	0.02 - 0.30, every step of 0.02	0.45, 0.60, 0.80, 1.00

148

149 **3. Results**

150 3.1 The needle lift characteristics

151 Fig. 3 shows the needle-lift profiles under the different injection-pulse durations and the injection
 152 pressures. It can be seen from the Fig. 3a that the needle-lift profile is separated into two stages, the
 153 opening stage and the closing stage. In the opening stage, the needle-lift profiles of different
 154 injection-pulse durations highly overlap, while in the closing stage needle-lift profiles seem parallel from
 155 each other. The duration of needle opening stage approximately equals to the injection-pulse duration. At

156 higher injection pressure, the needle opening speed increases and the needle can be lifted to the higher
 157 location. The above behaviors can be easily understood since the needle motion is mainly governed by the
 158 balance among the sac pressure, the spring force and the control chamber pressure. A stronger lifting force
 159 is conducted to the needle at higher injection pressure, thereby causing the needle moving faster. The
 160 injection-pulse duration only decides the timing to open and close the fuel release valve in the control
 161 chamber. Consequently, extending the injection-pulse duration will not alter the needle dynamics.

162 For further analysis, the needle speeds under different injection pressures are illustrated in Fig. 3b. It
 163 can be found that abrupt velocity peaks appear at the beginning and closing of the needle movement. This
 164 phenomenon should be attributed to the driven mode of the injector to ensure the precise control of needle
 165 opening and closing. Except these regions, the needle opens and closes both with almost constant speeds.
 166 However, the needle opening speed is dependent on the injection pressure. The higher injection pressure
 167 increases the needle opening speed. In contrast, the needle closing speed is insensitive to injection
 168 pressure.

169

(b)

FIG. 3. The needle lift profiles and speed at different injection-pulse durations.
(a) needle lift profiles; (b) needle lift speeds ; (SOI means start of sending injection triggering signal)

3.2 The needle-lift dependence of near-field liquid-jet dynamics

On the basis of the needle motion investigations, the needle-lift dependence of jet dynamics will be discussed in the following section. Fig. 4 shows the profiles of jet axial velocity at different injection-pulse durations. In the Fig. 4a the needle-lift profiles were shown and their peaks were also marked for better illustration, while in Fig. 4b the axial velocity profiles at all injection-pulse durations were presented against the needle lift. Firstly, it can be seen from the figure that the profiles of jet axial velocity at different injection-pulse durations highly overlap. To specific, regardless of the injection-pulse duration, the axial velocity increases exponentially at the initial needle-opening stage. Then after the needle reaches certain critical height, the axial velocity becomes constant and steps into the steady state. During this steady state, no matter how further the needle lift increases or even partly decreases after reaching the peak, the axial velocity keeps unchanged. Varying the injection pressure, the steady-state axial velocity will increase, but the needle-lift dependence of axial velocity appears similar.

A critical needle lift, from which the jet axial velocity reaches the steady-state value, was defined and evaluated using the results of Fig. 4. The results show that the critical needle lift is around 80 μm for the current injector. It should be mentioned that this critical needle lift may vary when different injector driving schemes or nozzle hole geometries are applied. For the real engine conditions, a much higher critical height of needle lift should be adopted to guarantee the enough portion of fuel to be delivered with steady-state axial velocity. The existence of critical needle-lift clearly points out that in the multiple-injection strategies, the insufficient needle lift under the short injection-pulse duration may hurt the initial spray momentum and flow performance indeed and it should be highly aware of.

FIG. 4. The liquid-jet dynamics changing with needle lift at different injection-pulse durations:
 (a) needle lift vs. SOI; (b) needle motion vs. U_{axial} .

To further discuss the needle-lift dependence of liquid-jet dynamics, it should be noticed that there are actually two different stages, needle opening and closing stage. Whether the jet dynamics at the same needle-lift height but different stages differ or not will be discussed in the following paragraph.

In one aspect, it can be seen from the Fig. 4b that, at the peaks of different needle-lift profiles, there is no obvious sudden change in corresponding jet axial velocity, which indicates that the jet dynamics in the near-nozzle field can be predominated by the needle lift, no matter the needle is rising or declining. The result of jet expansion angle (θ) in Fig. 5a further supports the adequacy of above explanation. It can be seen

from the figure that the θ in the opening and closing stage is basically equal. Someone may notice that the spray expansion angle seems to be negative at some timings. It should be explained that at present the jet structure imaging has been finished only at one location (nozzle exit) and the spray expansion angles were calculated accordingly. It can be seen from Fig. 2c that under the current experimental condition the high-speed liquid jet breakups little even until 1mm except that some surface wrinkles generate in the jet. These surface wrinkles may decrease the jet width sometimes. Besides that, it is also believed that initial flow angle can be less than zero when the vena-contracta reaches outside the nozzle. With more breakups of jet, the spray expansion angle will enlarge again in the far field.

We extend the discussion to the transient period, in which the needle lift is below the critical value. Fig. 5b compares the profiles of axial velocity during the opening and closing stage when the needle lift is lower than 0.1 mm. It can be seen from the result that, under the same injection pressure, the profiles of axial velocity during two stages are similar, but there is slight difference. In the opening stage, jet doesn't come out from the orifice exit until the needle lift is higher than 0.03mm approximately. This phenomenon can be easily understood because certain needle lift is needed for the sac-pressure generation. The situation in the closing stage is different. The sac pressure decreases gradually until the needle is fully closed. Therefore, even the needle is lower than 0.03 mm (real limit of data acquisitions is 0.01 mm) relatively high-speed jet still exists and more velocity data can be acquired. Besides velocity measuring data, third-order polynomial curve fitting method have been adopted and the local maxima is calculated as $H_{critical}$ using the second-order derivative test. It can be seen from the results that the needle-lift at which the jet axial velocity reaches its maximum in the opening stage ($H_{critical-open}$) is larger than that in the closing stage ($H_{critical-close}$). The reason for this phenomenon may attribute to the different hydraulic conditions in the sac during the needle opening and closing.

FIG. 5. Comparison of the jet dynamics between opening and closing stage:
(a) liquid-jet expansion angle; (b) profiles of axial velocity at low needle lift.

4. An one-dimension model on the axial velocity in the near-nozzle field

A simple one-dimensional analytical model was established to predict the jet axial velocity during the injection process based on the pressure variation inside the sac. The analytical model in this study was derived from the theory of bulk modulus. Several investigations with the similar method have been seen in literatures [32-33]. Compared to those investigations, the model in current study is greatly simplified but still with good prediction accuracy. It is also the first time that this kind of method was simulated with the

real needle motion data and validated thoroughly by experimental data of nozzle exit velocity from different nozzles. The details of our model will be presented in the following section. The pressure variation inside the sac can be calculated using Eq. 1 under the consideration of fuel compressibility.

$$\Delta p = E * \Delta V / V \quad (1)$$

where Δp is the derivative of pressure, E is the bulk modulus of liquid fuel, V is the volume, and $\Delta V / V$ is the relative derivative of volume. For diesel fuel, E equals to 2.0×10^9 Pa. Fig. 6a shows presents the idealizing method of nozzle internal geometry and Fig. 6b shows the geometrical factors and variables used in the analytical model. The sac chamber, which was adopted for simulation, was ideally described as two parts, a cylinder and a half sphere. The cylinder and sphere share the same bottom surface with a radius of r_{sac} and the height of cylinder is h_s . From the figure, it can be seen that the idealized geometrical model highly matches with the real nozzle structure. In the real nozzle sac chamber, there are actually two small volumes on the upper corner in both sides. Based on our simulation results, these volumes showed limited effect on the velocity calculation results (less than 3%) and were ignored for simplification. In our model, we assumed that ΔV equals to the deviation between the mass flow rate of fuel passing through the needle valve seat ($\dot{m}_{NV}$) and the nozzle orifice ($\dot{m}_O$) as shown in Eq. 2.

$$\Delta V = \dot{m}_{NV} - \dot{m}_O \quad (2)$$

FIG. 6. Sketch of model parameters definition:
(a) nozzle geometry idealizing method; (b) model geometrical parameters definition.

The mass flow rate of $\dot{m}_{NV}$ and $\dot{m}_O$ can be calculated by introducing Bernoulli's equation of fluid dynamics, as presented in Eq. 3 and Eq. 4.

$$\dot{m}_{NV} = C_{dNV} * A_{NV} * \sqrt{2 \times (P_{in} - p) / \rho_f} \quad (3)$$

$$\dot{m}_O = n * C_{dO} * A_O * \sqrt{2 \times (p - P_b) / \rho_f} \quad (4)$$

where A_{NV} denotes the inlet area of fuel coming into the sac through the needle valve seat, A_O is the

orifice outlet area. $C_{d_{NV}}$ and C_{d_o} is the flow discharge coefficients through the nozzle valve seat and nozzle orifice. P_{in} and P_b are the injection pressure and back pressure, respectively, ρ_f is the fuel density and n is the number of orifices inside the nozzle. In view of the needle movement, the area A_{NV} and the sac volume (V) change with the needle lift (L). Two equations were employed to calculate the variation of the A_{NV} and V with L , as presented in Eq. 5 and Eq. 6. It should be mentioned that Eq. 5 and Eq. 6 would be different and more complicated when the needle tip moves away from the sac region during the injection process. However, based on the experimental data we found that the axial velocity can step into the steady state at quite low needle lift where the needle tip is still within the sac. Consequently, for simplification of our calculation we assumed that the needle tip is always within the sac.

$$A_{NV}(L) = \pi \times r_{sac}^2 - \pi \times (r_{sac} - L \times \tan\alpha)^2 \quad (5)$$

$$V(L) = V_0 - \frac{1}{3}\pi \times (h_{ini.} - L) \times (r_{sac} - L \times \tan\alpha)^2 \quad (6)$$

In the equation, α denotes the half angle of the needle tip, V_0 is the sac volume without needle, $h_{ini.}$ is the initial height of needle tip from the sac inlet. The needle lift data presented in Fig. 3a were used as the model input.

In Eq. 4, C_{d_o} is the discharge coefficient of fuel passing through the nozzle orifice, which normally can be obtained by measuring the mass flow rate at nozzle exit using some commercial instruments. Its calculating formula is presented as Eq. 7.

$$C_{d_o} = \frac{\dot{m}_o}{M} = \frac{U_{exp.}}{\sqrt{2 \times (p - P_b) / \rho_f}} \times C_{a_o} \quad (7)$$

In this equation, M means the theoretical mass flow rate and $U_{exp.}$ is the mean fuel velocity at nozzle exit, C_{a_o} is the area contraction coefficient at orifice outlet, which is close to 1 in laminar flow state. It has been found in this study that the fuel jets in the near-nozzle field develop in pure-liquid state and expand little in the lateral direction. Consequently, it is reliable to regard the jet axial velocity (U_{axial}) as the exit velocity ($U_{exp.}$) and to assume C_{a_o} as 1 for simple estimation. Then the Eq. 7 can be replaced by Eq. 8. In this study, based on the experimental velocity data, C_{d_o} is approximately 0.940 for 100MPa and 0.936 for 200MPa. It should be mentioned that as a simplified model, current simulation didn't consider the cavitation effect in detail. However, when the cavitation phenomenon generates inside the nozzle, the variation of C_{d_o} can also show some evidences of cavitation existence and indirectly reveal its influence on jet. Besides that, the fuel properties effects, including the fuel density, viscosity and vapor pressure, actually will also be reflected to the C_d and have been included indirectly in our model.

$$C_{d_o} = \frac{U_{axial}}{\sqrt{2 \times (p - P_b) / \rho_f}} \quad (8)$$

In Eq. 5, C_{d_N} is the discharge coefficient of fuel passing through the needle valve seat. However, apart from the situation of orifice discharge coefficient, the discharge coefficient of needle valve seat is

very difficult to be measured and rarely evaluated previously in literatures. In our analytical model, we assumed it as the model parameter. Firstly, different values of C_{dNV} have been adopted in the simulations to analyze its effect on the numerical results, as shown in Fig. 7. It can be seen that the selection of C_{dNV} greatly influences the initial shape of the simulation curve, but it presents little effect on the steady-state axial velocity. A value of 0.25 was found for best fitting to current experimental data.

FIG. 7. Effect of model parameter C_{dNV} on the simulation results

As mentioned previously, the injection-pulse duration becomes much shorter in the multiple-injection strategies. Therefore, it is very important to consider the jet dynamics at limited injection-pulse duration. Fig. 8 reveals the simulation results of jet axial velocity at short injection-pulse durations. It can be seen from the figure that even at the critical needle-lift regions the simulation results based on our model match well with the experimental profiles. Moreover, by introducing the experimental results of needle motion as simulation input, the current model can also reveal the difference of jet axial velocity between the needle opening stage and closing stage. It should be mentioned that at the time of 0.1 ms after SOI, due to the insufficient needle lift (lower than 0.03mm, as shown in FIG 3a), fuel injection haven't begun yet. Therefore, no data are presented within that period.

FIG. 8. Simulation results at different injection-pulse durations with parameter $C_{d_{NV}} = 0.25$

For further validation, Fig. 9 shows the comparison between the numerical and experimental results of jet axial velocity based on different nozzles. The referenced experimental data were derived from previous investigation [27]. It can be seen from the figure that, when applying the corresponding model to the different nozzles' cases, the model parameter $C_{d_{NV}}$ should be slightly adjusted according to the experimental results for the best fitting. This can be easily understood that the different internal structure of nozzle alters the nozzle internal flow characteristics. It still should be emphasized that, by introducing the mass flow rate equilibrium equation to evaluate the pressure variation of nozzle sac, the current simple analytical model has achieved a good agreement in the prediction of the jet axial velocity in the near-nozzle field, which firmly proves the needle lift dependence of jet dynamics and also clearly unveil its influencing mechanism.

FIG. 9. Nozzle effect on model parameter $C_{d_{NV}}$

Someone would notice that the current value of $C_{d_{NV}}$ in our model seems much lower than the value of C_{d_o} ($0.6 \sim 1.0$, according to References 15, 16, 34). The reasons for this may lie in the fact that, in this study we focused the transient of jet dynamics in short injection-pulse duration. During this stage, the needle valve is opened quite insufficiently and the Couette flow may exist. Under the Couette flow state, the flow passing through the needle valve seat is greatly affected by the fuel viscosity and becomes apparently slow, which would result in the reduction of the discharge coefficient. Therefore, it is reasonable that $C_{d_{NV}}$ is smaller than C_{d_o} .

5. Conclusions

In this study, by taking advantage of the XPCI technique, the in-nozzle needle motion and the liquid-jet dynamics in the near-nozzle field in a wide range of injection-pulse durations have been measured. Based on the results, the needle-lift dependence of liquid-jet dynamics, especially the jet axial velocity, was discussed in detail. The critical needle-lift height, from which the liquid jets can obtain the sufficient initial momentum and flow rate, was also defined. It can be drawn from the above investigations that:

- 1) The needle opening speed is highly dependent on the injection pressure, while the needle closing speed is much less sensitive. Under the same injection pressure, extending the injection-pulse duration did not alter the needle dynamics.
- 2) No matter the needle is opening or closing, the near-nozzle liquid-jet dynamics is predominated by the needle lift and the injection pressure. Insufficient needle lift under the short injection-pulse duration may jeopardize the jet momentum and flow rate indeed. To obtain the steady-state jet axial velocity under the corresponding injection pressure, the needle lift peak should be higher than 80 μm for current investigated injector.
- 3) By introducing the mass flow rate equilibrium equation to evaluate pressure variation of nozzle sac, an analytical model is developed to predict the jet axial velocity in the near-nozzle field. The adequacy of the proposed model is widely validated by the experimental data, which provides deep insight into the influencing mechanism of needle lift on the liquid jet dynamics.

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REFERENCES

- [1] Delacourt E, Desmet B, Besson B. Characterisation of very high pressure diesel sprays using digital imaging techniques. *Fuel* 2005;84:859-867.
- [2] Wang X, Huang Z, Zhang W, Kuti OA, Nishida K. Effects of ultra-high injection pressure and micro-hole nozzle on flame structure and soot formation of impinging diesel spray. *Applied Energy*. 2011;88:1620-1628.
- [3] Naber J, Siebers D. Effects of Gas Density and Vaporization on Penetration and Dispersion of Diesel Sprays. SAE Paper 960034.
- [4] Klein-Douwel RJH, Frijters PJM, Seykens XLJ, Somers LMT, Baert RSG. Gas density and rail pressure effects on diesel spray growth from a heavy-duty common rail injector. *Energy and Fuels*. 2009;23(2):1832-1842.

- [5] Frédéric B, Seers P. Impact of physical properties of biodiesel on the injection process in a common-rail direct injection system. *Energy Conversion and Management* 2009;50:2905-2912.
- [6] Mohan B, Yang W, Yu W. Effect of internal nozzle flow and thermo-physical properties on spray characteristics of methyl esters. *Applied Energy*. 2014;129:123-134.
- [7] Linne M. Imaging in the optically dense regions of a spray: A review of developing techniques. *Progress in Energy and Combustion Science*. 2013;39:403-440.
- [8] Cung K, Moiz A, Johnson J, Lee SY, Kweon CB, Montanaro A. Spray-combustion interaction mechanism of multiple-injection under diesel engine conditions. *Proceedings of the Combustion Institute*. 2014:3061-3068.
- [9] Salvador FJ, Carreres M, Jaramillo D, Martínez LJ. Comparison of microsac and VCO diesel injector nozzles in terms of internal nozzle flow characteristics. *Energy Conversion and Management* 2015;103:248-299.
- [10] Molina S, Salvador FJ, Carreres M, Jaramillo D. A computational investigation on the influence of the use of elliptical orifices on the inner nozzle flow and cavitation development in diesel injector nozzles. *Energy Conversion and Management* 2014;79:114-127.
- [11] Hiroyasu, H, and Arai, M, Structure of fuel sprays in diesel engine. SAE Paper 900475.
- [12] Desantes JM, Payri R, Salvador FJ, Morena, JDL. Influence of cavitation phenomenon on primary break-up and spray behavior at stationary conditions. *Fuel* 2010;89:3033-3041.
- [13] Payri R, Salvador FJ, Gimeno J, Novella R. Flow regime effects on non-cavitating injection nozzles over spray behavior. *International Journal of Heat and Fluid Flow*. 2011;32(1):273-284.
- [14] Huang WD, Wu ZJ, Gong HF, Gao Y, Deng J, Li LG. Effect of nozzle geometry on macroscopic behavior of diesel spray in the near-nozzle field SAE Paper 2013-01-1587.
- [15] Lucio Postrioti, Francesco Mariani, Michele Battistoni. Experimental and numerical momentum flux evaluation of high pressure Diesel spray. *Fuel* 2014;98:149-163.
- [16] Salvador FJ, Carreres M, Jaramillo D, Martínez LJ. Analysis of the combined effect of hydro grinding process and inclination angle on hydraulic performance of diesel injection nozzles. *Energy Conversion and Management* 2015;105:1352-1265.
- [17] Roisman IV, Araneo L, Tropea C. Effect of ambient pressure on penetration of a diesel spray. *International Journal of Multiphase flow*. 2007;33:904-920.
- [18] Som S, Ramirez AI, Longman DE, Aggarwal SK. Effect of nozzle orifice geometry on spray, combustion, and emission characteristics under diesel engine conditions. *Fuel*. 2011;90(3):1267-1276.
- [19] Wang TC, Han JS, Xie XB, Lai MC, Henein NA, Schwarz E, Bryzik W. Parametric Characterization of High-Pressure Diesel Fuel Injection Systems. *Journal of Engineering for Gas Turbines and Power*. 2003;125:412-426.
- [20] Payri R, Gimeno J, Viera JP, Plazas AH. Needle lift profile influence on the vapor phase penetration for a prototype diesel direct acting piezoelectric injector. *Fuel* 2013;113:257-265.
- [21] Margot X, Hoyas S, Fajardo P, Patouna S. CFD Study of Needle Motion Influence on the Spray Conditions of Single-Hole Injectors. *Atomization and Sprays* 2011;21:31-40.
- [22] Taghavifar AH, Shervani-Tabar MT, Abbasalizadeh M. Numerical study of the effects of injector needle movement and the nozzle inclination angle on the internal fluid flow and spray structure of a group-hole nozzle layout. *Applied Mathematical Modelling* 2015;39:7718–7733.
- [23] Salvador FJ, Martínez LJ, Caballer M, Carreres M, Alfonso CD. Study of the influence of the needle lift on the internal flow and cavitation phenomenon in diesel injector nozzles by CFD using RANS methods. *Energy Conversion and Management* 2013;66:246-256.
- [24] Powell CF, Kastengren AL, Fezzaa K, Liu Z, Fezzaa, K. The Effects of Diesel Injector Needle Motion on Spray Structure. *Journal of Engineering for Gas Turbines and Power* 2011;133:012802 1-9.
- [25] Moon S, Tsujimura T, Gao Y, Park S, Wang J, Kurimoto N. Biodiesel effects on transient needle motion and near-exit flow characteristics of a high-pressure diesel injector. *International Journal of Engine Research*. 2013;15:504-518.
- [26] Moon S, Gao Y, Wang J, Fezzaa K, Tsujimura T. Near-field dynamics of high-speed diesel sprays: Effects of orifice

- inlet geometry and injection pressure. *Fuel* 2014;133:299-309.
- [27] Moon S, Gao Y, Park SP, Wang J, Kurimoto N, Nishijima Y. Effect of the number and position of nozzle holes on in- and near-nozzle dynamic characteristics of diesel injection. *Fuel* 2015;150:112-122.
- [28] Alan K, Christopher PF, Zak TF, Liu ZP, Moon S, Zhang XS, Gao J. End-of-Injection Behavior of Diesel Sprays Measured With X-Ray Radiography. *Journal of Engineering for Gas Turbines and Power* 2012;134:094501 1-4.
- [29] Seoksu Moon, Xusheng Zhang, Jian Gao, Kamel Fezzaa, Eric Durfresne, Jin Wang, Xingbin Xie, Fengkun Wang, Ming-Chia Lai. Morphological exploration of emerging jet flows from multi-hole diesel injectors at different needle lifts. *Atomization and Sprays* 2015;25:375-396.
- [30] Wang ZM, Ding HC, Ma X, Xu HM, Wyszynski ML. Ultra-high speed imaging study of the diesel spray close to the injector tip at the initial opening stage with split injection. *Applied Energy* 2016;163:105-117.
- [31] Cung K, Moiz A, Johnson J, Lee SY, Kweon CB, Montanaro A. Spray-combustion interaction mechanism of multiple-injection under diesel engine conditions. *Proceedings of the Combustion Institute* 2015;35:3061-3068.
- [32] Y.H. Zhu, R.D. Reitz. Modeling Fuel System Performance and Its Effect on Spray Characteristics. *SAE Paper* 2000-01-1253.
- [33] E. Plamondon, P Seers. Development of a simplified dynamic model for a piezoelectric injector using multiple injection strategies with biodiesel/diesel-fuel blends. *Applied Energy* 2014;131:411-424.
- [34] R. Payri, J.M. García, F.J. Salvador, J. Gimeno. Using spray momentum flux measurements to understand the influence of diesel nozzle geometry on spray characteristics. 2005;84:551-561.