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Spray Tip Penetration of Inversed-delta Injection Rate Shaping in Non-Vapourising Condition

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ABSTRACT

The performance and emissions of diesel engine are highly depending on the fuel delivery process thus, injection rate shaping approach is expected to be crucial in the development of a highly efficient and clean modern engine. A novel rate shaping injector called TAIZAC (TAndem Injection Zapping ACtivation) is used to realise an injection rate shaping of progressive ramp-down of high initial injection pressure as in inversed-delta shape. This study aims to investigate diesel spray tip penetration behaviour in inversed-delta injection rate shaping. The experiments are conducted under a high-density non-vapourising condition in a constant volume combustion chamber. High-speed diffused back illumination DBI imaging of the diesel spray is acquired at 30,000 fps using mercury lamp as the light source. The tip penetration of the inversed-delta injection is smaller than that of rectangle injection regardless of their injection momentum which is proportional to t0.5 and t0.43 in rectangle and inversed-delta injection case, respectively. To examine the potential of inversed-delta injection on wall heat loss reduction, diesel spray flame impinges to a MEMS sensor located at 28-mm downstream. It is interesting to note that the heat flux in 200 MPa inversed-delta injection is reduced by approximately 15% compared to 200 MPa rectangle injection even though their tip penetration starts to diverge at approximately 30 mm; indicates the TAIZAC injector potential in improving engine thermal efficiency.

Keywords: Injection rate shaping; diesel spray, tip penetration, inversed-delta; TAIZAC.

INTRODUCTION

Modern diesel engine tends to employ small orifices injector to meet stringent emission regulations. Better fuel atomization and subsequently fuel-air mixing can be achieved by coupling small nozzle orifices with high-pressure injection. Nishida et al. reported that by combining micro-hole nozzle of 0.08 mm diameter with ultra-high injection pressure up to 300 MPa, ambient air flow rate into the spray was enhanced and soot formation was reduced [1]. However, due to smaller orifices flow area, injection duration is elongated, increasing combustion duration results in a reduction of constant volume degree and thermal efficiency especially at the high-load operating condition. Further increase of injection pressure in an attempt to reduce this elongated injection duration result in higher

NOx emissions and harsh engine knocking [2]. Thus, it is necessary to investigate the main cause of late combustion and propose an effective mitigation method.

From our previous simultaneous high-speed imaging of soot luminosity, UV radiation and UV laser diffused back illumination (DBI) experiment, diesel late combustion was identified at the rich mixture stagnating at the spray tip [3]. Arai et al. explained that the following spray catch-up with the forepart spray, likely because the spray tip velocity is slower due to momentum exchange between the spray head and surrounding high-density stagnant air; the faster following spray, either pushing the former spray laterally or mixing together to form the spray tip rich mixture downstream [4][5]. Zama et al conducted a time-resolved PIV method in non-vapourising diesel spray and confirmed that the following spray velocity is faster than the spray tip [6]. In order to suppress the spray tip rich mixture, continuous injection rate ramp-down as in inversed-delta shape is proposed. By reducing the following spray momentum, the spray tip catch-up motion can be reduced and the fuel can be distributed evenly within the spray.

Johari and Paduano speculated that during the decelerating period, ambient fluid entrainment is increased to compensate for the decreasing jet axial flow [7]. A simple one-dimensional analysis during deceleration phase by Musculus has revealed that the air entrainment is increased up to three times at end of injection EOI or transient decelerating period compared to quasi-steady period [8][9]. This effect produced a very lean mixture nearby injector nozzle that might not be able to combust especially in low-temperature combustion case where ignition delay is longer than the injection period [10]. It is mentioned that the entrainment magnitude is controlled by the deceleration rate, where aggressive ramp-down as in high pressure and ultra-fast needle closing during EOI transient period promotes the highest air entrainment. By carefully controlling the injection rate profiles, one might be able to tailor the desired mixing states of the spray at a given time [11][12]. Thus, progressively reducing the injection rate during the injection event might possibly enhance air entrainment and results in faster combustion duration for conventional diesel combustion.

Direct control of needle lift by using a direct-acting piezo-actuated injector has been reported to be able to control the fuel flow and effectively tailor the injector rate shaping. Several research groups showed that injection rate shaping achieved by using piezo-stack injector is capable to control macroscopic spray development and tip penetration of diesel spray thus widen up the possibility to control the diesel combustion characteristics [13][14]. However, the piezo-actuated injector is relatively expensive and difficult to use for continuous engine cycle test. The recent development of HiFORS rate-shaping injector also showed that injection rate shaping has a high potential to alter diesel spray behaviour and improve engine thermal efficiency [15]. In this study, a novel injector called TAIZAC (Tandem Injector Zapping Activation) is designed and manufactured in-house by connecting two commercial injectors directly to each other [16]. By controlling the actuation timing of the two injectors, the supply of common rail high pressure can be isolated and stored as hydraulic pressure in the injector inner chamber. Furthermore, its size is comparable to the commercial injector and can be mounted on the engine head and run continuously for engine performance tests.

Schematic diagram of the conventional top hat or rectangle and expected inversed-delta diesel spray is depicted in Figure 1 [17]. Since constant injection momentum is supplied in rectangle injection following spray easily catch up with the previously injected spray parcel due to intense spray-air momentum exchange at the spray head and low local density induced by thermal expansion of hot spray. On the other hands, owing to lower following spray injection pressure in inversed-delta injection, lesser momentum is available to propel the spray head much further [18]. A lower tip penetration is speculated to reduce the cooling loss to the wall thus increase overall engine thermal efficiency.

Diesel spray behaviour such as mixing and combustion is considered to be controlled by ambient air entrainment [4]. Recently, time-resolved particle image velocimetry PIV method has been developed to examine the instantaneous air particle direction and magnitude during very short diesel injection event where Eagle et al. had successfully measured the increased of entrainment after EOI transient compared to the quasi-steady period [19]. Although it is relatively difficult to directly measure the microscopic behaviour of the spray such as air entrainment amount, it is much simpler to measure the spray macroscopic behaviour such as spray tip penetration and spreading cone angle that is directly related to air entrainment [4]. Perhaps the most well-known spray tip relation to other spray characteristics has been published by Wakuri et al. which show the spray tip penetration is directly proportional to $t^{0.5}$ from the spray momentum conservation theory as shown in Eq. (1) [20]. This theory holds valid for quasi-steady spray even in modern diesel injector. Hiroyasu et al. have improved the equation by introducing the spray tip penetration equation before fuel break-up length as in Eq. (2) and Eq. (3) [21].

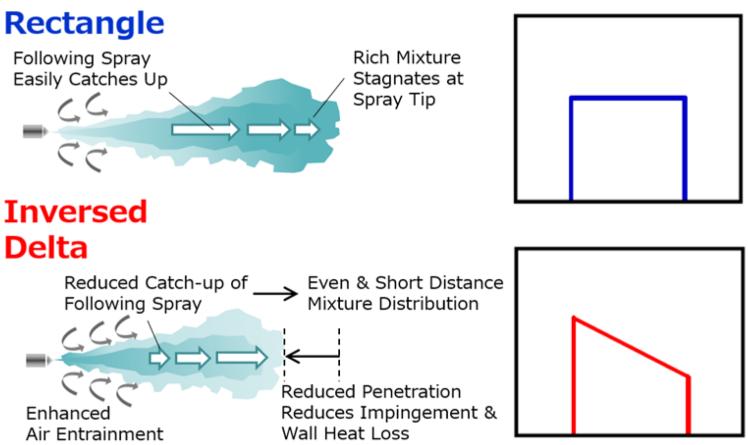


Figure 1. Schematic diagram of diesel spray flame characteristics of conventional rectangle injection (top) and expected with inversed-delta injection (bottom).

$$x = \left(\frac{2c\Delta P}{\rho_a}\right)^{0.25}\left(\frac{td}{\tan\theta}\right)^{0.5} \tag{1}$$

$$S = 0.39\sqrt{\frac{2\Delta P}{\rho l}.t} \qquad (0 < t < t_b) \tag{2}$$

$$S = 2.95\left(\frac{\Delta P}{\rho_a}\right)^{1/4}\sqrt{D_n}\sqrt{t} \qquad (t_b < t) \tag{3}$$

In order to develop a better understanding on transient inversed-delta injection spray behaviour, a simple macroscopic study on inversed-delta and rectangle injection spray tip penetration are conducted in a high-density non-vapourising condition where the injection conditions are set up similar to high-load operating conditions.

EXPERIMENTAL SETUP

In this section, a brief explanation on TAIZAC injector and non-vapourising diffused back illumination (DIB) setup were carried out.

TAIZAC: TAndem Injector Zapping ACtivation Injector

TAIZAC schematic diagram and operating principles are shown in Figure 1 where the details are discussed in another publication [16]. Two commercially available injectors were directly connected; namely, DENSO third-generation piezo injector G3P is used as upper injector and for lower injector, DENSO fourth-generation solenoid injector G4S body was cut and tightened together with an in-house fastening part. Ideally, G3P injector is preferred for their superior actuation response however, to achieve faster ramp-down rate it is necessary to reduce the injector inner volume. G4S injector has a relatively small actuation part that are compacted near the needle region, allowing for higher dead volume removal than the G3P injector.

By controlling the actuation timing of both injectors, one can realise the injection rate shaping desired. For example, as shown on the right side of Figure 2, continuous injection ramp-down rate as in inversed-delta rate shaping can be achieved by first actuating upper injector needle to supply the injector with common-rail pressure. Then by closing the upper injector needle, we are able to charge the lower injector with hydraulic pressure while cutting off direct pressure supply from the common rail. Once lower injector was actuated, fuel was injected initially at high pressure then gradually decreases as the accumulated hydraulic pressure decreases. By actuating both injectors at approximately the same time, present rectangle injection can be achieved.

Injection rate shaping profiles obtained with Bosch-type long tube method from multi orifices injector is presented in Figure 3. Table 1 shows the injection conditions where the total relative momentum of the injected fuel is derived from the total injection rate and the actual injection duration was confirmed with high-speed laser DBI at 100,000 fps in atmospheric condition. The injection pressure was measured with a strain gauge attached to the lower injector body.

Table 1. Injection conditions.

Pattern	Pressure (MPa)	Rate shaping	Duration (ms)	Momentum ($kgms^{-1}$)
200 MPa rectangle	200	Rectangle	1.06	0.001964
150 MPa rectangle	150	Rectangle	1.32	0.001660
200 MPa inversed-delta	200 to 100	Inversed-delta	1.34	0.001630
150 MPa inversed-delta	150 to 10	Inversed-delta	1.77	0.001337

Non-vapourising High-speed Diffused Back Illumination DBI Imaging Setup

Diesel combustion experiment was conducted in a constant volume combustion chamber CVCC equipped with three 35-mm-diameter quartz windows and an injector mounted at its head. Table 2. shows the experimental conditions for this study. Since the effective view field is relatively small compared to the whole spray length, distance z from the injector nozzle tip to the view field centre were varied from z=20, 55 and 90 mm where the obtained images are assembled together to mimic a whole spray. White light from a mercury lamp is diffused before entering the vessel and the high-speed images are acquired at 30,000 fps with 4 µs shuttering gate by using a NAC MEMRECAM HX-5 high-speed camera equipped with Nikkor 105 mm f2.8 lens as shown in Figure 4.

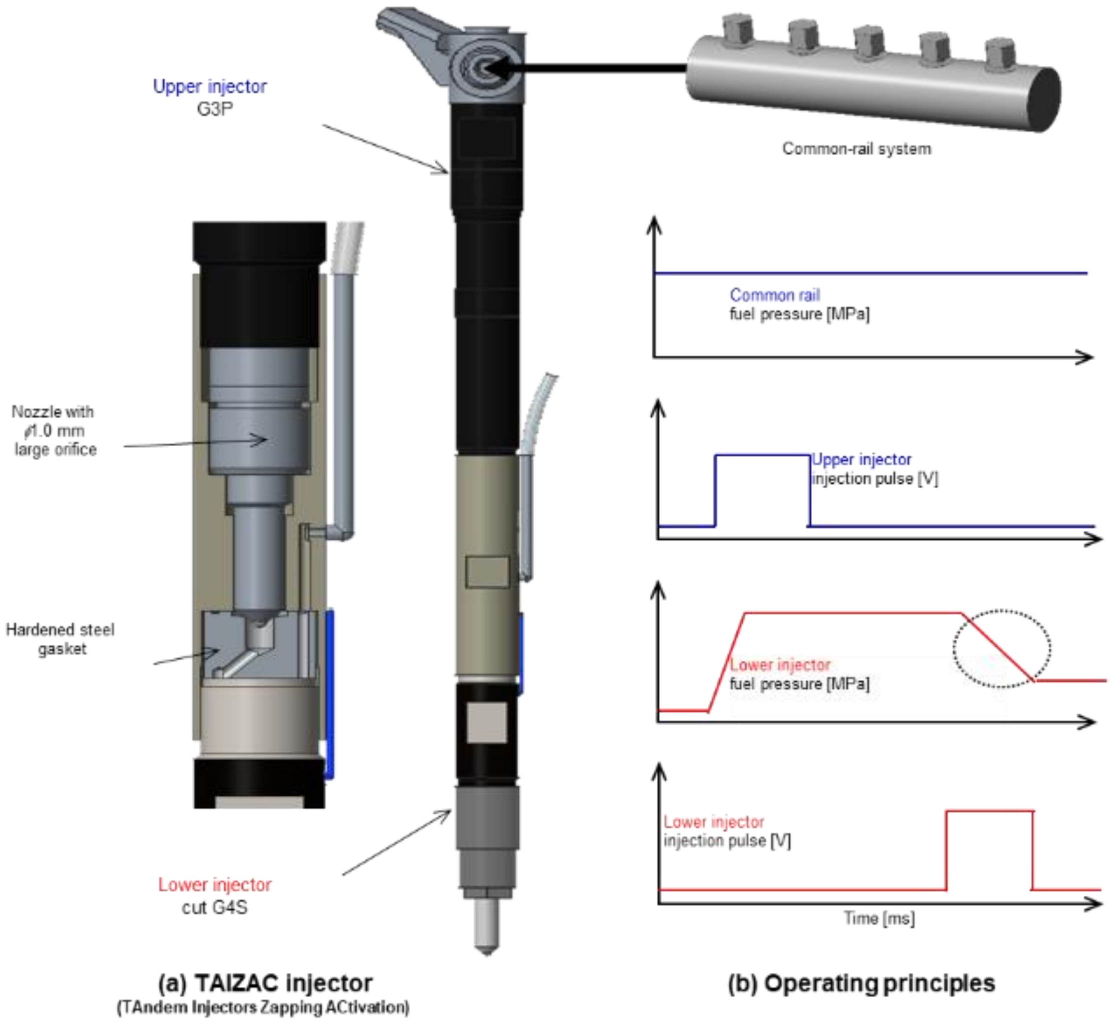


Figure 2. Schematic diagram of TAIZAC injector and its operating principles.

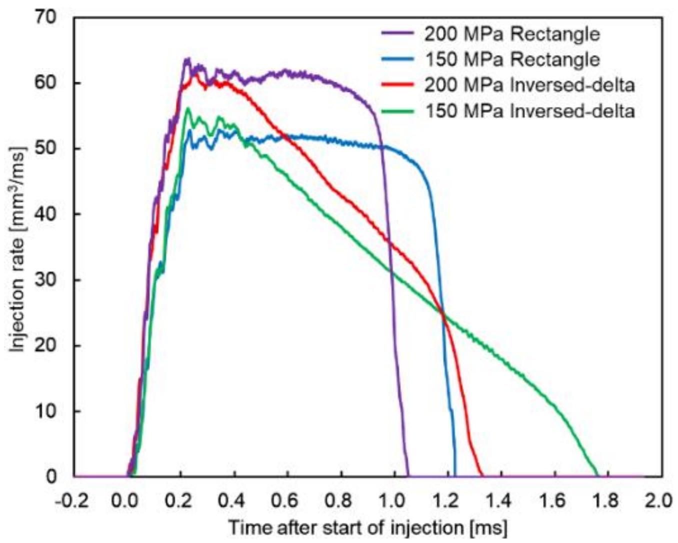


Figure 3. Inversed-delta and rectangle injection rate shaping profiles.

Table 2. Experimental conditions.

	Unit	Value / notes
Ambient gas density, ρ_a	kg/m^3	23.8
Ambient temperature, T_a	K	373
Ambient pressure, P_a	MPa	1.6
Ambient CO_2 concentration	Vol. %	100
Nozzle		φ0.12 mm x 8 + 1
Fuel		JIS2

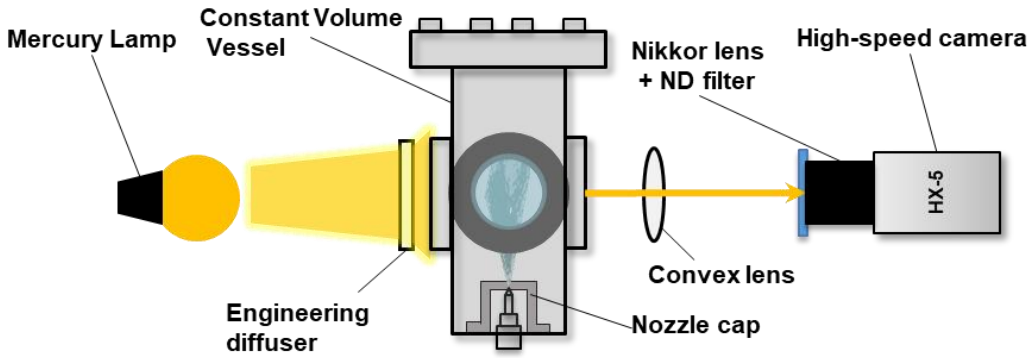


Figure 4. Experimental setup for free-spray high-speed diffused back illumination DBI.

Figure 5 shows the image processing and analysis method for the tip penetration used in this study. The top image is the raw image obtained from three different locations at the similar time after the start of injection ASI and the bottom image is the processed image obtained by dividing the image with the background image before the start of injection. Average signal value from 80 x 4-pixel size area is calculated along the spray axis and 10% threshold level is used to determine the spray tip penetration where 1 pixel is equivalent to 0.0875 mm.

In order to extract only one spray from the TAIZAC injector, the additional orifice is drilled axially on the nozzle tip and a nozzle cap is attached to block another spray from radial orifices. It is examined only 3.4 mg is measured from axial orifice while the fuel mass injected from other 8 orifices is totalled at 41.6 mg. This small flow coefficient is likely caused by inner sac turbulence due to the peculiar axial orifice location. Furthermore, no hydraulic grounding is performed during the machining process.

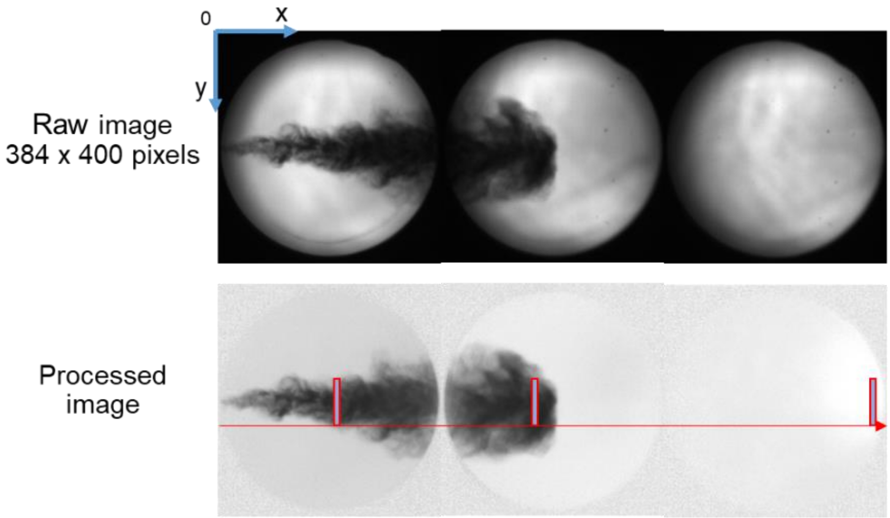


Figure 5. Example of spray tip penetration image processing and analysis.

RESULTS AND DISCUSSION

In this section, details on qualitative and quantitate analysis of spray tip penetration of inversed-delta and rectangle injections are discussed, followed by the investigation of tip penetration effects on wall heat flux measurement.

Spray Tip Penetration

Figure 6 showed the example of high-speed DBI images of 150 MPa rectangle and 200 MPa inversed-delta injection in non-vapourising condition acquired at 30,000 fps. Axial distance from nozzle orifice and time after the start of injection ASI is depicted at the bottom of the column and at top-left of each image sequence, respectively. From the images, it can be observed that initially, 200 MPa inversed-delta penetrates faster than 150 MPa rectangle. However, from approximately 2.0 ms time ASI and 60 mm axial distance, the inversed-delta spray seems to be slowed down where the rectangle spray penetration surpassed it. It is suggested that injection rate shaping might also be an important parameter in determining spray tip penetration.

In conventional rectangle injection, the following spray travels faster due to the fact that the spray tip is slowed down by the momentum exchange between the spray and the surrounding high density still air. Thus, the following spray caught up with the former spray and push the spray tip penetration further [4],[5]. However, in inversed-delta injection, the following spray is expected to travel at a slower velocity due to its decelerating injection rate.

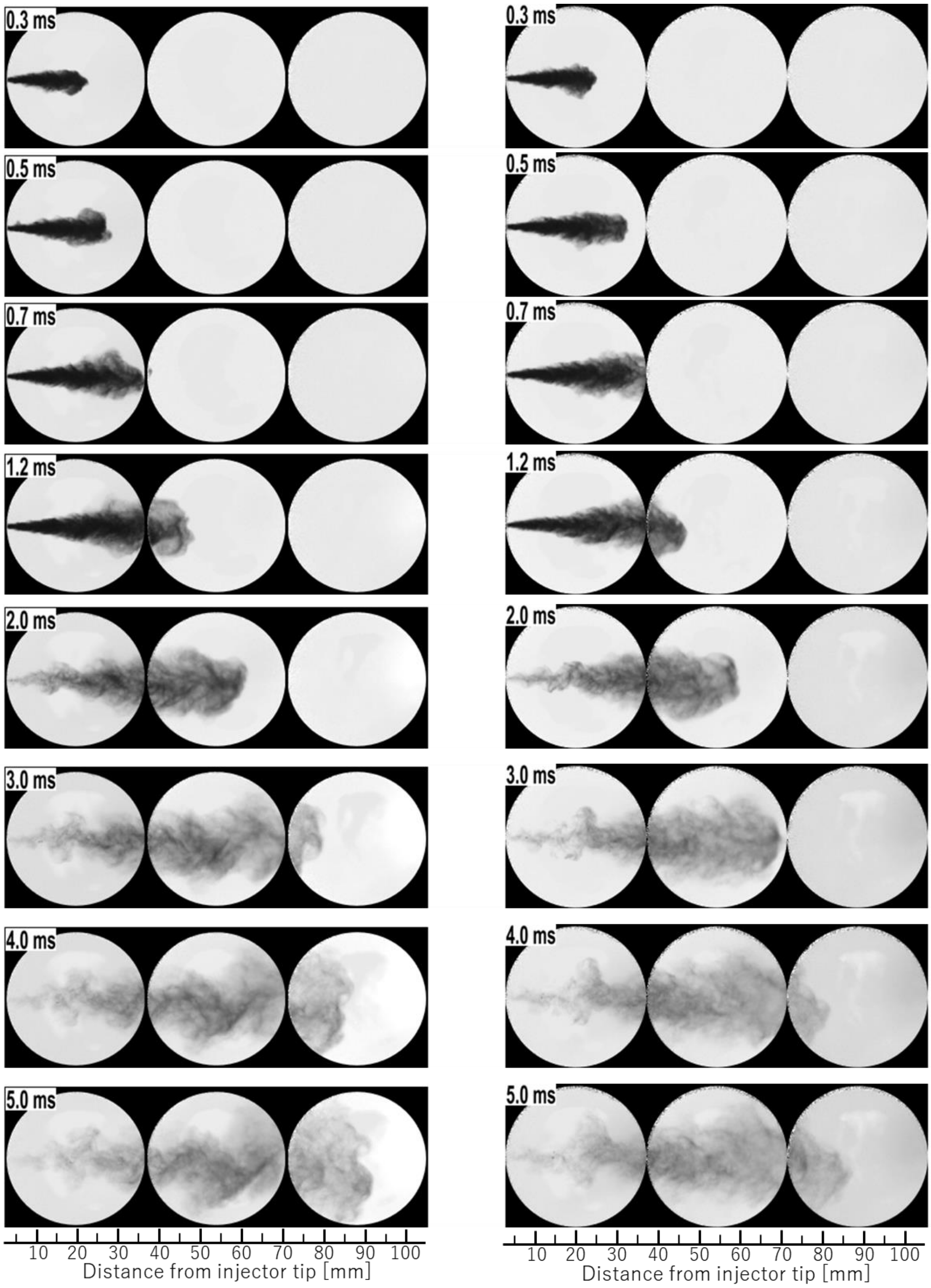


Figure 6. Example images of high-speed DBI in non-vapourising condition of (left) 150 MPa rectangle and (right) 200 MPa inversed-delta injection. Ambient conditions: ρ_a=23.8 kg/m^3, P_a=1.6 MPa, T_a=373 K and 100% CO_2. Injection conditions: φ0.12 mm orifice and m_f=3.4 mg.

Figure 7 shows the quantitative spray tip penetration extracted from the DBI images as shown in Figure 6. The spray tip penetration value is obtained by combining the ensemble average of 3 shots in three different axial locations; namely upstream, midstream and downstream. The total viewing field is from 2.5 mm to 117.5 mm and bumps observed at around 37.5 mm and 72.5 mm axial distance from the nozzle orifice are caused by different regions assembling artefact. The injection amount for each injection profiles are fixed at 3.4 mg and the respective injection duration is showed in Table 1.

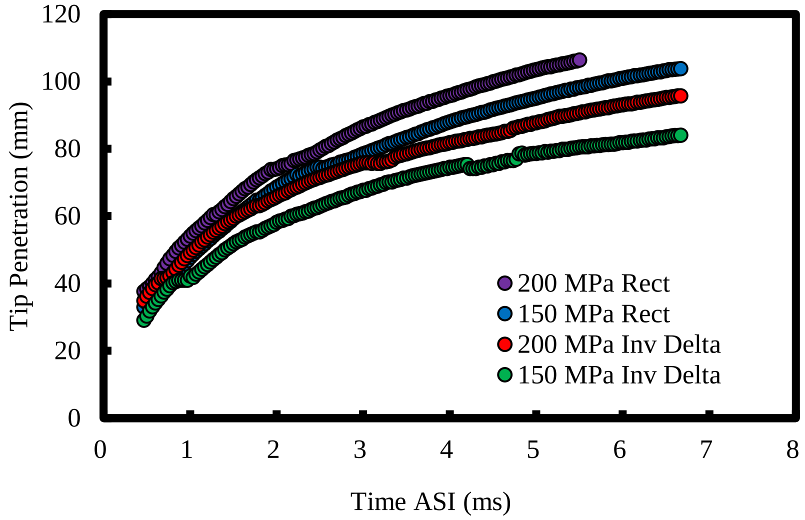


Figure 7. Spray tip penetration in non-vapourising condition.

Two injection pressures were tested for each injection profiles and the effects over spray tip penetration were examined. Increase of injection pressure increases the injected fuel momentum, thus the tip penetration increases as the injection pressure are increased in both rectangle and inversed-delta injection profile [18],[20]. By comparing the similar initial injection pressure conditions, it is observed that the spray tip seems to be travel at similar level initially before diverging out. As discussed previously, it is expected that the following spray has a lower momentum to push the spray tip penetration further in inversed-delta injection. It is interesting to note that the spray tip penetration of 200 MPa inversed-delta progress faster initially but it seems to be slowed down to which it is being surpassed by 150 MPa rectangle injection. As exposed in Table 1, the spray total momentum of 200 MPa inversed-delta and 150 MPa rectangle injection is almost similar. From the momentum view alone, the spray tip penetration of both cases should be comparable. However, it is clearly observed that the spray tip penetration of 150 MPa rectangle is longer than 200 MPa inversed-delta starting from a turning point and the difference becomes larger as it progresses further downstream. The spray penetration curve is similar for the same injection profile even at different injection pressure, but it seems to be at different with other injection profile.

The Wakuri's penetration equation based on the spray momentum conservation is valid for the spray penetration behaviour during an injection event [20]. Arai et al observed that just after the end of injection, the spray tip penetration seems to follow the Wakuri's equation to the timing where the transient spray affects the spray tip, mentioned as stagnating effects [4]. Furthermore, Musculus et al. expected that the end of injection event downstream affects the tip penetration at roughly half the injection duration after the EOI, likely due to the entrainment wave travelling downstream at twice the spray penetration velocity, reach the spray tip and slowing it down [9]. Figure 8 shows the spray tip penetration during the period where it is unaffected by the stagnating effects. Hiroyasu and Arai diesel penetration equation were plotted into the graph as the solid black lines. Noted that this equation is only valid for rectangle injection case since it is derived from momentum conservation theory in quasi-steady injection.

It can be observed that even in a non-typical injector used, the tip penetration data obtained here fit fairly well with the Hiroyasu and Arai equation with a slight overestimation likely due to the smaller flow coefficient value in the injector used in this study. The spray tip penetration in rectangle cases is proportional to $t^{0.5}$ as reported in the literature [18][19]. However, it is interesting to note that both 200 MPa and 150 MPa inversed-delta spray tip penetration are proportional to approximately $t^{0.43}$. Since the momentum along the spray axial direction is not conserved in inversed-delta injection, it is expected that the exponential value is different than that of rectangle injection. It is suspected that increased of air entrainment in transient ramp-down profile as in inversed-delta injection might promote fuel-air momentum exchange and slowed the tip penetration down further. Additionally, the exponential value seems to be dictated by the inversed-delta injection ramp-down rate. Thus, inversed-delta injection rate shaping might be a valuable tool for the automotive engineer to design the engine geometry. From the spray tip penetration results obtained, it can be predicted that the inversed-delta injection might not only improve combustion duration but also reducing cooling loss which increased the engine thermal efficiency.

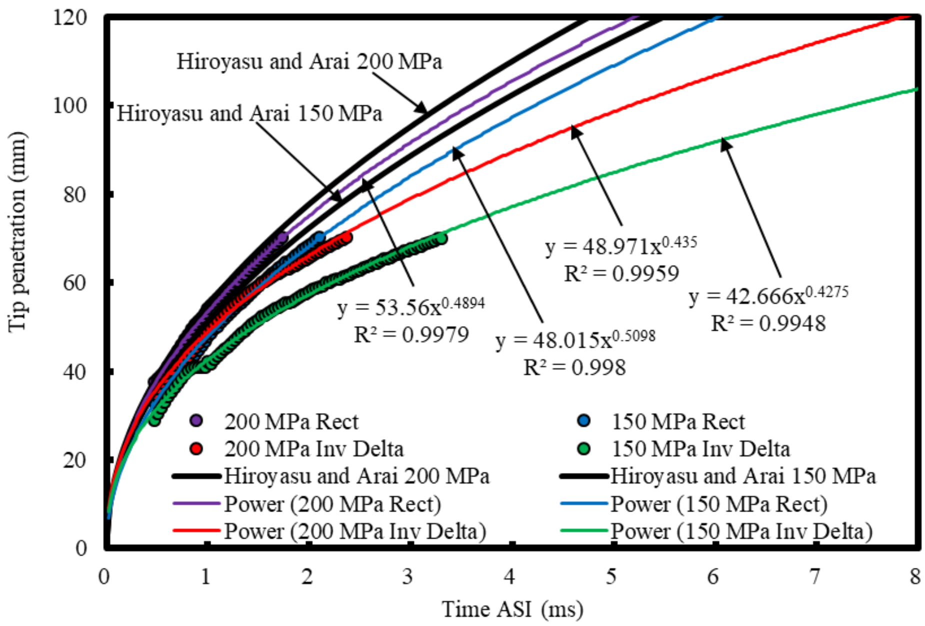
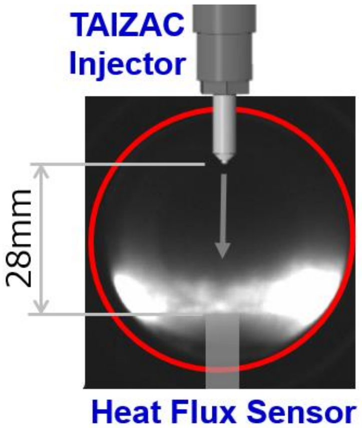


Figure 8. Spray tip penetration in non-vapourising condition before stagnating effects with Hiroyasu and Arai equation fitting [21].

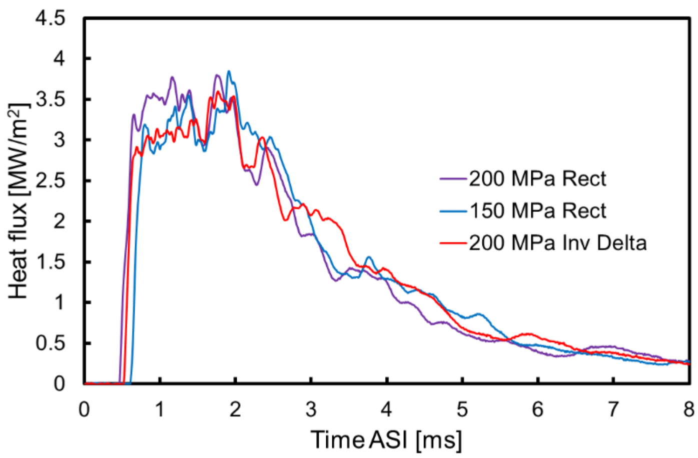
Heat Flux Measurement

Previously, shorter penetration observed in inversed-delta injection compared to rectangle injection. However, the penetration difference seems to be appreciated after spray penetrates beyond 40 mm which is much larger than most modern engine wall chamber bore radius thus it effects on wall heat loss might be limited. Currently, experiment on inversed-delta wall heat flux investigation in an optical engine via high-speed infrared thermal radiation is under preparation. Due to the complexity of the experimental setup and longer time frame, a simpler preliminary experiment was carried out to examine the potential of TAIZAC inversed-delta injection in reducing engine wall heat loss.

Figure 9(a) shows the experimental setup for the inversed-delta and rectangle diesel spray flame heat flux measurement. To produce diesel-like condition, premixed gases of acetylene, argon, carbon dioxide and oxygen were charged in the CVCC before being ignited with a spark plug, which 17 vol. % O_2 was produced as the combustion product. The pressure and temperature inside the chamber elevate and then decline due to heat transfer to the surrounding wall. Diesel fuel s injected at 4.5 MPa and 950 K and diesel combustion occurred due to high pressure and high-temperature conditions. A prototype thin-film Resistance temperature detector RTD type MEMS heat flux sensor with a diameter of 6 mm has developed for engine heat transfer investigation [23]. Diesel spray flame extracted from the axial orifice of TAIZAC injector directly impinged to this MEMS heat flux sensor at a distance of 28 mm which is comparable to a modern diesel engine bore size. As can be observed, an area of only 6 mm diameter is measured in this experiment even though the diesel spray flame spread to a relatively larger area after the wall impingement.



(a)



(b)

Figure 9. MEMS heat flux of directly impinging diesel spray flame at 28 mm axial distance experimental setup (a) and results (b).

Figure 9(b) exhibit the results of the heat flux of 200 MPa inversed-delta, 200 MPa rectangle and 150 MPa rectangle injection. The heat flux detection timing indicates by the heat flux value elevate is consistent with the spray tip penetration as in Figure 7 and Figure 8. Although the similar value of heat flux peak value is observed in 200 MPa inversed-delta and 150 MPa rectangle injection at approximately 3.0 MW/m^2, likely due to their similar total injection momentum as shown in Table 1. Nevertheless, it is interesting to note that the heat flux is reduced by approximately 15% in 200 MPa inversed-delta injection compared to 200 MPa rectangle injection, suggesting that the inversed-delta rate shaping by TAIZAC injector has a promising potential in reducing wall heat loss or cooling loss in an actual engine. However, careful consideration is needed to extract this heat flux data since the ignition delay in this experiment is relatively longer than that of the conventional diesel engine.

CONCLUSION

In this study, it was attempted to understand the inversed-delta spray behaviour from a simple spray tip penetration observation. The conclusions obtained are as follows:

i. Shorter total penetration is noted in inversed-delta rate shaping regardless of the total momentum injected. In similar total injection momentum case, the spray tip penetration is comparable initially but start to deviate gradually as it travels downstream.
ii. Spray tip penetration of rectangle injection is proportional with $t^{0.5}$ as typically reported in the literature, while the spray tip penetration of inversed-delta injection is proportional to $t^{0.43}$. It is speculated that the ramp-down rate might play an important role in governing the exponential value.
iii. Heat flux is reduced by approximately 15% in the inversed-delta injection case compare to rectangle injection at a similar initial pressure of 200 MPa. Thus, the potential of wall heat loss in the actual engine is anticipated by TAIZAC inversed-delta injection.

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