A review of diesel spray research

Mohd Al Hafiz Mohd Nawi¹, Wan Azani Mustafa¹, Muhammad Nazrin Shah Shahrol Aman¹, Syahrul Affandi Saidi¹, Ilham Shafini Mahyudin¹ and Mohd Aminudin Jamlos¹

¹ Faculty of Engineering Technology, Universiti Malaysia Perlis, Kampus UniCITI Alam, Sungai Chuchuh, 02100 Padang Besar, Perlis, Malaysia

Email: alhafiznawi@unimap.edu.my

Abstract. The following literature review provides an overview of research and a summary of the most condition that relevant to the present study. The overview focuses on such parameter such as the effect of ambient condition (density and temperature), the effect of fuel injection, the effect of injection pressure, the effect of mass fuel and effect of nozzle diameter that probably effects into the droplets distribution, spray evaporation and mixture formation of diesel spray. The preferred format has been choosing to allow an easier scanning and classification which intend to summarize the relevant topic and study regarding the diesel spray fields.

1. Introduction
Spray formation in diesel engine was one of the factors that influence the ignition starting, combustion process and, further, it also produces such of pollutant emission from the exhaust. Due to these circumstances, the spray formation is dependent on the few factors such as ambient density, ambient temperature, injection conditions etcetera. In order to analyze the spray characteristic, observation on spray at the condition as close as possible to an actual engine has been set-up. In this review, ambient density and temperature have been the main point to further investigate the effect on spray formation. In the same way, the influence of injection pressure and nozzle hole diameter also be considered in this study. It would clearly show how far the correlation on the spray formation was an effect.

2. Effect on diesel spray
2.1. Effect of ambient density and temperature of diesel spray
As a conclusion from a previous study [1–9] can be concluded as a brief explanation below. Effect on the ambient density of spray was significantly changed the spray behavior. As for the penetration length when ambient density increases the penetration tends to reduce. This conditions is due to the effect of entrainment air in the spray and increases spray dispersion. Further, the progressing spray shows slowing on tip penetration at high ambient pressure. One of the other hand under high ambient temperature conditions, it led to reducing the spray dispersion angle which mostly effects in spray core region [10]. As for droplets, the behavior is totally different at the main and tip spray due to the effect on aerodynamics interactions of ambient conditions [11]. Further, the droplets size distributions as the droplets formation affected by ambient pressure inside the spray chamber are clearly be seen in Fig. 1
[12]. It shows that, the droplets size decrease with increase spray length. The correlation of droplets size distributions with spray depth region would be seen in each discussion in this study.

As for being pointed by [13] that was shown in Fig. 2 [13], when high injection pressure has applied on high ambient pressure, the more homogenous mixture was obtained. This conditions will cause the promotion of internal mixing as increase ambient pressure [14]. Moreover, due to these circumstances, the surrounding gas was entrained into the spray. The momentum of droplets was decreased as the momentum was transferred to the entrained gas [13]. The motions are probably an increase of shear force as ambient pressure inside of spray chamber was rises [15]. In addition, at low ambient temperature, the droplet seen to flying away and leave evaporation trail [16]. However, when the ambient temperature increased the droplet numbers are decreased due to abridgment of the evaporation process [16]. Another essential point, the spray vapor phase is increased as the increase of the ambient conditions. This circumstance clearly is seen in [1] on this study when high ambient temperature at high ambient pressure was being applied. Whereas, affected by high ambient temperature would promote an enlarge vapor phase area as the quantity of fuel injection was lower [10].

2.2. Effect of nozzle hole diameter of diesel spray

Several studies [17–20] has been done according to the nozzle hole diameter. In summary, the spray characteristic such as breakup length, droplet sizes distribution, spray angle has been changing that affected by nozzle hole diameter. As the influence of the nozzle geometry will changing the essence of cavitation and turbulence inside the nozzle hole diameter. The probably for cavitation to ensue will be lower and for turbulence, it will reduce the turbulence level which appropriating longer breakup length [21].

![Figure 1. Sauter mean diameter at various sampling positions [12].](image1)

![Figure 2. Sauter mean diameter at various sampling positions [12].](image2)
Figure 2. Effect of ambient pressure on air excess ratio in a diesel spray [13].

According to this matter, the velocity profile, spray atomization, and injection rate will also change. In addition, effects on orifice shape also cause the flow in laminar or turbulence condition. As an example, an orifice with convergent shape cause greater gas phase fuel penetration compares with an orifice with a divergent shape [21]. Rarely, the length of the high-density region will reduce due to the decreasing the nozzle hole diameter. Furthermore, due to the small orifice diameter will lead to very tiny droplet sizes. It also increases the air-fuel mixing where the liquid fuel is in large fuel evaporation. It will give an improved atomization and permit faster rates of air entrainment [22]. In the same way, the effect on injection pressure will ensure large or small fuel evaporation and droplet size distribution. As a conclusion, applying higher injection pressures would result in improved fuel-air mixing and improved fuel atomization. Due to this reaction, the premixed combustion and the mass fuel burning rate increased significantly. Moreover, if the temperature is rising slowly at TDC, the fuel energy would release immediately. The thermal efficiency of the engine would also increase.

2.3. Effect of high injection pressure of diesel spray

The capability to control the combustion process are significantly related to the injection control of the fuel delivery process into the combustion chamber. Therefore, it is very important to understand the details of the relation between engine distinctive, spray behavior and the injection controller. In fact, applying higher injection pressure is a solution to reduce pollutant emissions and improve the performance engine. In a conventional engine, an injection pressure of 100 MPa was considered as high pressure. However, nowadays injection pressure that applies more than 160 MPa until 300 MPa has been considered as a high-pressure condition. Effect on this high pressure will make the droplets size on breakup regime become tinier. Furthermore, since the injection pressure increases the evaporation have also increased and prevented the droplet from flying away [16]. In addition, the droplet seems to stay still inside the vapor phase region [16]. Initially, by increasing the fuel injection pressure, it will change the behavior of spray atomization onwards increases engine performance and reduction in pollutant emissions [23]. Figure 3 [24] the correlations of the evolution of increasing injection pressure with droplet size formation since the early 1920s until 2020s. Here, we can say that by applying fuel at low injection pressure will enlarge the droplet size and further will lengthy the ignition delay period. For overcome this situation, it can be done by enforcing the fuel at high injection pressure condition. Hence, the NOx and CO emissions tend to decrease. In addition, it will change the atomization behavior which resulting in more issue of vapor phase and good mixing [25] which lead lower of CO emission and smoke level.

Also, by increasing the injection pressure, the droplet sizes become tinier, fuel atomization has shown improvement and the mixing of fuel-air will improves. This transition condition can clearly be seen since in Fig. 4 [26] the early 1970s until 2000s. Likewise, if the injection pressure is too high, the combustion efficiency decrease due to the worsens mixing process. Further, the effect on high injection pressure will lead to an increasingly high length penetration on spray [2,27]. The fuel injection pressure in the range from 100 to 300 MPa is typically being study according to the injection system applied. Otherwise, fuel velocity injections also increase. Due to this, the droplet movement and gas entrainment inside combustion chamber will also change. Hence, we must keep in mind that excellent on injection duration control has a significant effect on the entire regime process. For that reason, the rate of unburned HC and NOx can be reduced. If the injection duration is in retarded, the incomplete combustion and higher unburned HC emissions will form [28]. The fuel consumption will more worthwhile. Then again, if the injection duration it took too long, the particulate emission and excessive smoke would produce. Due to this condition, the multiple injection strategies of pilot injection is a solution. It will greatly benefit to overcome the particulate emission and NOx.
2.4. Effect of multiple injection of diesel spray

Nowadays, new technology on injection systems is the capability to hold and perform high extreme condition in the combustion chamber. This injection strategy is allowed to enforce multiple injection strategies such as pilot injection, main injection and post-injection like as shown in Fig. 5. Hence, multiple injections have been introducing to decrease particulate emissions significantly without a rise in NOx emissions [29]. The correlation of injection strategies is related to the needle lift. Captions are set in 9-point type. If they are short, they are centered between the margins. Longer captions, covering more than one line, are justified. Captions that do not constitute a full sentence, do not have a period. Pilot Injection - Short injection with a small amount of fuel before the start of the main injection is called pilot injection. It resulted in pre-conditioning of the combustion chamber before the combustion process is taking place. Due to this benefit, the mass of fuel will evaporates quickly and propose the ignition reaction ready to takeoff. As a result, by the implement pilot injection strategies, it will reduce NOx emissions and combustion noise.

In particular, setting on span time between the pilot and the main injection is very important. If the pilot is close-by to the main injection, the fuel has less time to mix and it would make low effectiveness on noise reduction, However, less soot has found at the diffusion burning [30]. The fuel quantity may also be affected during the combustion process. If the fuel amount is too large, it can increase the particulate matter and if the fuel amount is too small and too early, it would raise the

---

**Figure 3.** Period of Combustion Process [24].

**Figure 4.** Diesel fuel injection trends [26].
combustion noise. Further, based on a previous study [31], the researcher suggested an amount of 1 to 3 mg per stroke anywhere up to 90° CA could improve the efficiency of the combustion. Subsequently, pilot injection could result in a modest increase of soot due to the lower initial temperature, high diffusion burning and less premixed burning [1]. This condition can also be quenched by applying post injection strategies. Based on the previous study, a combination of pilot injection with higher injection pressure will reduce 35% on NOx and 60-80% on smoke without deteriorating the fuel consumption [32]. Other studies have found out the NOx emissions reduced to 30% and significantly reduce to half of HC at optimum condition disputes for black smoke level have kept constant [33].

Main Injection - A standard fuel injected into the spray combustion chamber is normally known as the main injection. This phase injection is proposed on engine torque and power. The injection rate also depends on the injection pressure. At this period, employing an ideal type injection of the square, ramp and boot would offer economy fuel consumption likes as shown in Fig. 6 [34]. According to this type of injection, the square type has shown high length penetration compared to others. Noted that, the test has been set-on same fuel quantity, in addition, it seems no changes of spray cone angles at different type injection [34]. Furthermore, in another study [2] the boot type injections resulted in low NOx emissions as with soot and fuel consumption was higher. Figure 7 [35] shows the characteristics parameters of boot type of injection such as boost pressure, length, and duration [36]. Same authors also studied on engine combustion affected by fuel rate shaping. They identify that by changing the rate shape phase at boot type injection it would changing the diffusion combustion phase. Moreover, it would reduce NOx at high load and speed conditions [37].

![Figure 5. Schematics of multiple injections implement](image)

![Figure 6. Ideal square, ramp and boot type injections (reproduce from [36] as adopted from [34])](image)
Post Injection - The injection strategies has been applied while after the main injection. The post injection should immediately be injected after the main injection to obtaining reduce HC, smoke and fuel consumption. This injection strategy is very effective to reduce soot emissions (up to 70% reduction) [38]. Small fuel amount with high injection pressure would carry out large kinetic energy that proposes an effective mixture formation on combustion.

2.5. Effect of injection strategies on emission of diesel spray
As we already know, based on the previous subtopic, the effect of high injection pressure will form great fuel atomization and evaporation. It also improves the combustion process and producing less of particulate emission. However, the influence of high injection pressure will tend to increase NOx emission during the combustion process. This subtopic will review on emission as affected by high injection pressure. Study on soot at high ambient condition (high temperature & high pressure) affected by injection pressure has been done by Pickett and Siebers [39]. They find out when injection pressure increased the soot levels will be decreased. This is because the fuel-air mixture and the amount of air entrainment have been decreased. Due to these circumstances, it will occur onerous of the lift off the length. Further, the effect on high injection velocity will decrease time dwelling on the soot regions. Same goes on a study by Agarwal et al. [40] when increasing high injection pressure and advancing on injection timing [41] the concentration of particulate number have been cut down. Setting in injection timing will provide more time for air-fuel mixture especially on droplets distribution before the combustion occurs. One of the other application in injection strategies is ultra-high injection pressure. The effect on this circumstance on the flame structure and soot formation have been presented by [18]. Based on Fig. 8, [18] have reported that soot luminosities and flame size were appreciably smaller at an injection pressure of 2000 and 3000 bar compare with 1000 bar. The soot and luminosity show much stronger. Furthermore, when the grey scale intensities of all pixels have been integrated on soot luminosity they find out the reduction in soot luminosities as pressure injection rise from 1000 to 2000 bar. However, at injection pressure rise up to 3000 bar, there was no change at all. From here, it can be concluded that the rise in injection pressure will result in improved spray atomization and better air entrainment. Therefore, the soot was also reduced.

A significant study on exhaust particulate emission has been done by [42]. Their study discovered on non-volatile particle emission when the injection pressure was applied. They have found out the dry particle size will change their sizes in all loads condition. Moreover, the number of particles increased an increase in injection pressure. In addition, a certain that particulates size was around 5nm as in high injection pressure while in normal size it was below than 5 nm. Besides, at medium loads, the size lower than 5 nm was dependent on how much load it has been applied. As a conclusion, the reduction of soot and NOx emissions was rise due to increasing injection pressure. In the same way, the NOx emissions can be avoided as pilot injection strategies have been employ while soot emissions will be reduced as pre-injection was applied. Furthermore, [36] have pointed out that the NOx emissions can be offset by using rate shaping and retarded the injection timing.
3. Conclusion
This paper mainly focuses on the effect of various variables on the spray characteristic of diesel spray. Each sub-topic above has summarize on all probably occured when involves with certain variables on the spray behavior such as spray atomization, evaporation and droplet behavior during ignition delay period. A brief introduction due to current energy consumption, pollutant emission problem have also been discuss on this paper review. This review would be significant knowledge regarding future engine development influence with fuel injection strategies.

4. References
[1] Nawi M A M, Kidoguchi Y, Nakagiri M, Uwa N and Nada Y 2014 Macro- and Micro-scale Observation on Dynamic Behavior of Diesel Spray Affected by Ambient Density and Temperature 1–9
[2] J. Naber D S 1996 Effects of Gas Density and Vaporization on Penetration and Dispersion of Diesel Sprays SAE Tech. Pap.
[3] Payri R 2005 Determination of Diesel Sprays Characteristics in Real Engine In-Cylinder Air Density and Pressure Conditions
[4] Payri R, Salvador F J, Gimeno J, Morena J De and Valencia U P De 2008 Macroscopic Behavior of Diesel Sprays in the Near-Nozzle Field 1 528–36
[5] Valentino G, Alfuso S, Montanaro A, Corcione F E, Caputo G, Allocca L and Auriemma M 2005 Analysis of a High Pressure Diesel Spray at High Pressure and Temperature Environment Conditions SAE Technical Paper Series vol 1
[6] Delacourt E, Desmet B and Besson B 2005 Characterisation of very high pressure diesel sprays using digital imaging techniques Fuel 84 859–67
[7] Crua C, Kennaird D A, Sazhin S S, Heikai M R and Gold M R 2004 Diesel autoignition at elevated in-cylinder pressures Int. J. Engine Res.
[8] Cárdenas M, Martin D and Kneer R 2010 Experimental Investigation of Droplet Size and Velocity in Clustered Diesel Sprays under High-Pressure and High-Temperature Conditions SAE Technical Paper Series

Figure 8. Formation on soot formation and flame size at end of injection (adopted from [18]).
[9] Manin J, Bardi M, Pickett L M, Dahms R N and Oefelein J C 2014 Microscopic investigation of the atomization and mixing processes of diesel sprays injected into high pressure and temperature environments Fuel 134 531–43

[10] Nawi M A M, Uwa N, Ueda Y, Nada Y and Kidoguchi Y 2015 Droplets Behavior and Evaporation of Diesel Spray Affected by Ambient Density after Pilot Injection SAE Tech. Pap.

[11] Payri F, Desantes J M and Arrégle J 1996 Characterization of D.I. Diesel Sprays in High Density Conditions Sae

[12] Hiroyasu H and Kadota T 1974 Fuel Droplet Size Distribution in Diesel combustion chamber (SAE) Tech. Pap. 740715 2615–24

[13] Manaka Y, Ohta T, Saito M and Furuhata T 2009 Effect of High Ambient Pressure on Behavior and Structure of Diesel Spray International Annual Conference on Liquid Atomization and Spray Systems, Vail, Colorado, USA pp 1–6

[14] Arai M 2015 Diesel Spray Penetration and Air Entrainment 1–8

[15] Arai M 2012 Physics behind Diesel Sprays Iclass 1–18

[16] Adam A, Inukai N, Kidoguchi Y and Miwa K 2007 A Study on Droplets Evaporation at Diesel Spray Boundary during Ignition Delay Period 1379–89

[17] Zhu J, Kuti O A and Nishida K 2012 An investigation of the effects of fuel injection pressure, ambient gas density and nozzle hole diameter on surrounding gas flow of a single diesel spray by the laser-induced fluorescence-particle image velocimetry technique Int. J. Engine Res.

[18] Wang X, Huang Z, Zhang W, Kuti O A and Nishida K 2011 Effects of ultra-high injection pressure and micro-hole nozzle on flame structure and soot formation of impinging diesel spray Appl. Energy 88 1620–8

[19] Nishida K and Zhang W 2007 Effects of Micro-Hole and Ultra-High Injection Pressure on Mixture Properties of D. I. Diesel Spray 1353–61

[20] Yoda T and Tsuda T 1997 Influence of Injection Nozzle Improvement on DI Diesel Engine

[21] Ashgriz N 2011 “Handbook of Atomization and Sprays: Theory and Applications”

[22] Badami M, Nuccio P and Trucco G 2010 Influence of Injection Pressure on the Performance of a DI Diesel Engine with a Common Rail Fuel Injection System SAE Technical Paper Series

[23] Wloka J A, Pflaum S and Wachtmeister G 2010 Potential and Challenges of a 3000 Bar Common-Rail Injection System Considering Engine Behavior and Emission Level SAE Int. J. Engines

[24] Majewski W 2012 DieselNet Technology Guide DieselNet.com

[25] Bruneaux G 2014 LIQUID AND VAPOR SPRAY STRUCTURE IN HIGH-PRESSURE COMMON RAIL DIESEL INJECTION At. Sprays

[26] Gulder O L 2014 VIEWS ON THE STRUCTURE OF TRANSIENT DIESEL SPRAYS At. Sprays

[27] Siebers D L 1998 Liquid-Phase Fuel Penetration in Diesel Sprays

[28] Jayashankara B and Ganesan V 2010 Effect of fuel injection timing and intake pressure on the performance of a di diesel engine - A parametric study using CFD Energy Convers. Manag.

[29] Herfatmanesh M R, Lu P, Attar M A and Zhao H 2013 Experimental investigation into the effects of two-stage injection on fuel injection quantity, combustion and emissions in a high-speed optical common rail diesel engine Fuel

[30] Russell M F, Greeves G and Guerrassi N 2010 More Torque, Less Emissions and Less Noise SAE Technical Paper Series

[31] Flaig U, Polach W and Ziegler G 2010 Common Rail System (CR-System) for Passenger Car DI Diesel Engines; Experiences with Applications for Series Production Projects SAE Technical Paper Series

[32] Anon Shundoh et al. - 1992 (NOx Reduction using Pilot Injection).pdf

[33] Dürnholz M, Endres H and Frisse P 1994 Preinjection A Measure to Optimize the Emission
Behavior of DI-Diesel Engine Preinjection A Measure to Optimize the Emission Behavior of DI-Diesel Engine

[34] Benajes J, Payri R, Molina S and Soare V 2005 Investigation of the Influence of Injection Rate Shaping on the Spray Characteristics in a Diesel Common Rail System Equipped with a Piston Amplifier J. Fluids Eng.

[35] Desantes J M, Benajes J, Molina S and González C A 2004 The modification of the fuel injection rate in heavy-duty diesel engines. Part 1: Effects on engine performance and emissions Appl. Therm. Eng.

[36] Mohan B, Yang W and Chou S K 2013 Fuel injection strategies for performance improvement and emissions reduction in compression ignition engines—A review Renew. Sustain. Energy Rev. 28 664–76

[37] Desantes J M, Benajes J, Molina S and González C A 2004 The modification of the fuel injection rate in heavy-duty diesel engines: Part 2: Effects on combustion Appl. Therm. Eng.

[38] C B 2006 Mixture Formation in Internal Combustion Engine (Berlin: Springer-Verlag)

[39] Pickett L M and Siebers D L 2004 Soot in diesel fuel jets: Effects of ambient temperature, ambient density, and injection pressure Combust. Flame

[40] Agarwal A K, Dhar A, Srivastava D K, Maurya R K and Singh A P 2013 Effect of fuel injection pressure on diesel particulate size and number distribution in a CRDI single cylinder research engine Fuel

[41] Agarwal A K, Srivastava D K, Dhar A, Maurya R K, Shukla P C and Singh A P 2013 Effect of fuel injection timing and pressure on combustion, emissions and performance characteristics of a single cylinder diesel engine Fuel

[42] Lähde T, Rönkkö T, Happonen M, Söderström C, Virtanen A, Solla A, Kytö M, Rothe D and Keskinen J 2011 Effect of fuel injection pressure on a heavy-duty diesel engine nonvolatile particle emission Environ. Sci. Technol.

Acknowledgements

The authors would like to express their gratitude to the Faculty of Engineering Technology (FETech) and Research Management Innovation Centre (RMIC) of Universiti Malaysia Perlis for the allocation of grant incentives for publication.