The effect of nozzle diameter, injection pressure and ambient temperature on spray characteristics in diesel engine

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Abstract. Mixture formation of the ignition process is a key element in the diesel combustion as it influences the combustion process and exhaust emission. Aim of this study is to elucidate the effects of nozzle diameter, injection pressure and ambient temperature to the formation of spray. This study investigated diesel formation spray using Computational Fluid Dynamics. Multiphase volume of fluid (VOF) behaviour in the chamber are determined by means of transient simulation, Eulerian of two phases is used for implementation of mixing fuel and air. The detail behaviour of spray droplet diameter, spray penetration and spray breakup length was visualised using the ANSYS 16.1. This simulation was done in different nozzle diameter 0.12 mm and 0.2 mm performed at the ambient temperature 500 K and 700 K with different injection pressure 40 MPa, 70 MPa and 140 MPa. Results show that high pressure influence droplet diameter become smaller and the penetration length longer with the high injection pressure apply. Smaller nozzle diameter gives a shorter length of the breakup. It is necessary for nozzle diameter and ambient temperature condition to improve the formation of spray. High injection pressure is most effective in improvement of formation spray under higher ambient temperature and smaller nozzle diameter.

Keywords: CFD, droplet diameter, penetration length, breakup length, nozzle diameter.

1. Introduction
Fuel injected into the chamber is important to the diesel engine because it influence the performance and emission. During combustion, a spray is simply the introduction of liquid into a gaseous environment through a nozzle such that the liquid, through its interaction with the surrounding gas and by its own instability, breaks-up into droplets [1]. Spray characteristics is known to significantly affect the combustion and emission processes in diesel engines. By optimizing spray characteristics, the raw emissions from the diesel engine which are mainly NOx and PM can be minimized [2-4]. Investigations into diesel sprays characteristics have concentrated on the effect of the spray characteristic on engine performance such as the spray tip penetration, break-up length and droplet size and velocity distributions [5]. The injection pressure has significant effect on spray liquid penetration [6]. The spray tip penetration gets longer as the injection pressure increases. This result is related to both higher quantity and higher velocity of the droplets at higher injection pressures [7]. Proportional to injection pressure, the spray penetrates faster at higher injection pressures [8]. The break-up length characterizes a point of discontinuity, where the spray changes from a zone of liquid (bulk liquid, or interconnected ligaments and droplets), to a finely atomized regime of droplets [9]. After the disintegration of the liquid column emerging from the nozzle, the generated droplets may further break-up into smaller ones as they move into the surrounding gas [10]. Development of this deformation leads to break-up into smaller droplets. The forces associated with dynamic pressure, surface tension and viscosity control the break-up of a drop [11-12]. However, CFD is a compromise tool being used to predict the critical part that cannot be done in experiment. In this research, the characteristics of spray diesel are investigated focusing on changing
ambient temperature, injection pressure with the different nozzle diameter by using Computational Fluid Dynamics. This simulation can capture droplet diameter, spray penetration and breakup length.

2. Simulation set up
The modeling flow chart shows in Figure 1 is the flow of simulation in ANSYS Fluent. The first stage is pre-processing consists of the flow problem in the simulation. Solver stage is complete the calculation of finite element model or solving of governing equation. Post-processing is a process of involving data gathering and visualization.

![Methodology and modelling flow chart](image)

**Figure 1.** Methodology and modelling flow chart

A rapid compression machine (RCM) was used to generate the actual diesel combustion over a wide range of temperature, pressure and swirl velocities. Figure 2 is a schematic diagram of RCM is shown, together with an outline of the fuel injection system. Figure 3 shows the combustion chamber cross sectional drawing in 3D. The RCM has a disc type combustion chamber with a diameter of 60mm and width of 20mm. The design focuses on injector nozzle and spray chamber.

![Experimental setup of RCM](image)

**Figure 2:** Experimental setup of RCM.

![3D section view of combustion chamber](image)

**Figure 3:** 3D section view of combustion chamber

The injector was modeled by using Solid Work. In this study the combustion chamber is a space where the spray formation occurs. The model of the injector only considered the tip of the nozzle. Figure 4 shows the 3D model of cross sectional area of the injector tip. Figure 5 shows the sections geometry of the combustion chamber. It is 1/6 section from the overall geometry as there are 6 nozzles in the actual
chamber and only 1/6 is adequate and considered sufficient for the simulation analysis. The assigned boundary condition was serving as the initiation and direct to the motion of the flow. Table 1 shows the solver setup of the simulation. The parameters that need to investigate are droplet diameter of particle, penetration length and breakup length.

### Table 1. Solver Setup

| Options       | Type                             |
|---------------|----------------------------------|
| Multiphase Model | Volume of Fluid                  |
| Time          | Transient                        |
| Model         | Viscous K-Epsilon Model          |
| Material      | Diesel Liquid                    |
| Boundary Condition | Injection Pressure = 40MPa, 70MPa, 140MPa |
|               | Temperature Inlet = 313Kelvin    |
|               | Pressure Outlet = 1MPa           |
|               | Temperature Outlet = 500K, 700K  |

**3. Result and discussion**

This analysis used two different diameters which is 0.20 mm and 0.12 mm. This simulation using several different ambient temperatures on 500 K and 700 K for every injection pressure simulate with 40 MPa, 70 MPa and 140 MPa. The objective for this simulation is to investigate the different form of spray characteristic that influence by the nozzle diameter, ambient temperature and injection pressure of diesel engine. The analysis of spray characteristic of this simulation is more focus to the droplet diameter, penetration length and breakup length that influence from the parameter use. Grid sensitivity was tested on the model with different grid sizes. The grid size divided into three levels which are coarse, medium and fine grids. Table 2 indicates the number of elements and nodes for each group of different grid sizes. Besides, the number of elements is ranging from 24997 to 114555 elements. The number of elements is obviously directly proportional to the numbers of nodes by ascending the level of grid sizes from coarse to fine with also level of smoothing from low to high.

### Table 2. Different grid sizes with its number of elements and nodes

| Grid Sizes | Number of Elements | Number of Nodes |
|------------|--------------------|-----------------|
| Coarse     | 24997              | 5175            |
| Medium     | 46249              | 9428            |
| Fine       | 114555             | 22495           |

Droplet diameter of the spray was being Figure 6 shows that at 40 MPa droplet diameter at 0.20 mm and 500 K parameter show more droplet size colour red represent to a big size droplet compared to the 0.12 mm 700 K. The droplet distribution size of 0.12 mm and 0.2 mm are shown in the Figure 7 and 8. As illustrated in the graphs, they show that the pattern of the distribution size of the droplet is parallel to each other. The higher of ambient temperature and injection pressure give the smaller droplet diameter. The result describe that slightly fuel injected in the chamber can cause a lower combustion. At the same time droplet diameter depend on the aerodynamic drag in the chamber it can affect the droplet diameter performed smaller when the air collision with the fuel.
| Injection pressure | 40 MPa | 70 MPa | 140 MPa |
|-------------------|--------|--------|--------|
| 0.12 mm nozzle diameter with 500 K ambient temperature |
| 0.12 mm nozzle diameter with 700 K ambient temperature |
| 0.20 mm nozzle diameter with 500 K ambient temperature |
| 0.20 mm nozzle diameter with 700 K ambient temperature |

**Figure 6.** Spray structure of droplet diameter produced by single nozzle, with colour scale represents the droplet diameter.
As the graph illustrate the penetration length at Figure 9 and Figure 10 using different ambient temperature for 0.12 mm and 0.2 mm nozzle diameter constantly increase with the time taken and both for temperature the penetration length not give much different. This is due to the range of between temperatures not too big. However, the injection pressure influences the spray penetration length, where variant injection pressure which is 40 MPa, 70 MPa and 140 MPa with ambient pressure 1 MPa at atmospheric pressure. As the higher pressure injector, the longer length penetration will influence. This is because the spray was resisted with the ambient pressure.

Figure 7. Graph of droplet size distribution of 0.12 mm

Figure 8. Graph of droplet size distribution of 0.2 mm

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Figure 9. Graph penetration length with nozzle diameter 0.12 mm

Figure 10. Graph penetration length with nozzle diameter 0.2 mm

Figure 11 and 12 show the graphs of breakup length with 0.12 mm and 0.2 mm nozzle diameter. There is fluctuation result on the temperature 500 K, where injection pressure 140 MPa and nozzle diameter 0.2 mm dramatically increase from the 1 mm stood up to the 2.3 mm. This is maybe due to the droplet did not breakup and its getting longer, this is call as the section of ligament. Compare to the temperature 700 K at the 140 MPa and 0.2 mm breakup length flows steady with the time. Thus the temperature influences to the higher ambient temperature used, the shorter breakup length happen at the core segment.
4. Conclusion

This study has shown a simulation flow of the fuel flowing in the nozzle spray before combustion. A low injection pressures in the chamber will disturb the breakdown of the fuel spray to a very fine droplets before start ignition of the fuel. A temperature change in the chamber also affects the length of the spray penetration. For high ambient temperatures, fuel evaporates more easily and ignites the fuel itself. Also, the diameter of the nozzle also affects the breakup length of the spray nozzle as influenced by the higher injection pressure where the breakup length is getting shorter.

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References

[1] Adam, A., Inukai, N., Kidoguchi, Y., Miwa, K. Et Al., 2007,"A Study on Droplets Evaporation at Diesel Spray Boundary during Ignition Delay Period," SAE Technical Paper 2007-01-1893.
[2] Khalid, A., Anuar, M.D., Ishak, Y., Manshoor, B., Sapit, A., Leman, M., Zaman, I., 2014“Emissions characteristics of small diesel engine fuelled by waste cooking oil”, MATEC Web of Conferences, Volume 13, Article number 06006, 2014, DOI: 10.1051/matecconf/20141306006
[3] Khalid, A., Tamaldin, N., Jaat, M., Ali, M.F.M., Manshoor, B., Zaman, I., 2013,“Impacts of Biodiesel Storage Duration on Fuel Properties and Emissions”, Procedia Engineering, Volume 68, Pages 225-230, Elsevier Ltd, DOI: 10.1016/j.proeng.2013.12.172.
[4] Khalid, A., Jaat, N., Sapit, A., Razali, A., Manshoor, B., Zaman, I., Abdullah, A.A., 2015,"Performance and emissions characteristics of crude jatropha oil biodiesel blends in a diesel engine” International Journal of Automotive and Mechanical Engineering, Volume 11, Issue 1, Pages 2447-2457, DOI: 10.15282/ijame.11.2015.25.0206.
[5] Khalid, A., Hayashi, K., Kidoguchi, Y., Yatsufusa, T., 2011,“Effect of air entrainment and oxygen concentration on endothermic and heat recovery process of diesel ignition”, SAE Technical Papers, Society of Automotive Engineers of Japan, Inc. and SAE International, DOI: 10.4271/2011-01-1834.
[6] Khalid, A., 2013, “Effect of Ambient Temperature and Oxygen Concentration on Ignition and Combustion Process of Diesel Spray”, *Asian Journal of Scientific Research*, Volume 6, Issue 3, Pages 434-444, Asian Network for Scientific Information, DOI: 10.3923/ajsr.2013.434-444.

[7] Camille Hespel, Jean-Bernard Blaisot, Xandra Margot, S. Patouna, Armelle Cessou, Bertrand Lecordier, 2010, “Influence of Nozzle Geometry on Spray Shape, Particle Size, Spray Velocity and Air Entrainment of High Pressure Diesel Spray”, *THIESEL*.

[8] I. V. Roisman, L. Araneo, and C. Tropea, 2007, “Effect of Ambient Pressure on Penetration of a Diesel Spray,” *International Journal of Multiphase Flow*, Vol. 33, No. 8, Pp. 904–920.

[9] Simon Martinez – Martinez, Fausto A. Sanchez – Cruz, Vicente R. Bermudez And Jose M. Riesco-Avila, 2010, “Liquids Spray Characteristic In Diesel Engine”, *In: Daniela Siano (Ed.). Fuel Injection*. Intech: Sciyo. 20 – 48 Pages.

[10] Ozg Ur O’guz Tas, Kiran, 2011, ”Experimental Study on Diesel Spray Characteristics and Autoignition Process”, *Hindawi Publishing Corporation*.

[11] Naber, J. And Siebers, D., 1996, “Effects of Gas Density and Vaporization on Penetration and Dispersion of Diesel Sprays,” *SAE Technical Paper* 960034.

[12] Andsaler, A.R., Khalid, A., Jaat, N., Izwan Sukarman, M., “Effects of ambient density on flow characteristics of biodiesel spray injection using computational fluid dynamics”, ARPN Journal of Engineering and Applied Sciences, Volume 11, Issue 8, Pages 5499-5505, 2016. http://www.arpnjournals.org/jeas/research_papers/tp_2016/jeas_0416_4142.pdf