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Analysis of Soot Particle Movement in Diesel Engine under the Influence of Drag Force

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Abstract. The formation of soot is influenced by the composition of air entrainment and structure of hydrocarbon in the fuel. Soot will then form during combustion in a diesel engine. Some of the soot particles will be released from the engine through the exhaust nozzle and some will stick to the cylinder walls. The soot that sticks to the cylinder wall can affect the lifetime of the lubricant oil. Subsequently this will decrease the durability of the diesel engine. By understanding the movement of the soot particles, the effect to the engine can be decreased. Therefore, the initial position and last position of soot particle was recognized through this study. The data for the formation of soot particles in the diesel engine was obtained from previous investigation. The study of soot movement at 8° crankshaft angle under the influence of drag force with different radial, axial and angular settings were carried out using a MATLAB routine. The results showed that the movement of soot particle will change with different parameter settings. Besides that, comparison of the results of soot particle movement influenced by drag force and without drag force has been carried out. It was observed that drag force caused shorter soot particle movement path and moves them away from the cylinder wall.

Introduction

Diesel engine has its drawbacks especially from an environmental perspective. Combustion in a diesel engine will release particulate matters (PM), nitrogen oxides (NO_x), sulfur oxides (SO_x) and noise emissions [1-4]. Particulate matter contains solid soot particles which will contaminate the lubricant oil, thus viscosity of the lubricant oil increases. Subsequently the walls of the combustion chamber will not be adequately coated which will increase its wear [5]. Besides that, when the viscosity of the lubricant oil increases, the interval between oil changes will decrease.

The wear mechanism due to the soot is still not fully understood, therefore fundamental study about this area is needed. Previous researchers investigated on soot distribution in a diesel engine by using the CFD software, Kiva-3v. Kiva-3v is reliable software to simulate the soot formation in a diesel engine combustion chamber [7-9]. Kiva-3v implements a two stage of Hiroyasu soot model in the simulation. The two stage soot models are for soot formation and soot oxidation [10]. Mahmood [6] carried out a soot particle size prediction along its path using combination of Hiroyasu's soot formation [11] and Nagle and Strickland-Constable soot oxidation [12] rate expression. Meanwhile, Hong et al [13] also developed a model for soot formation process in diesel engine but the result of the model was different to the experimental result. Other mechanisms that occur in the cylinders that causes soot deposition are thermophoresis, inertial deposition, electrophoresis and gravitational sedimentation. Among those mechanisms, thermophoresis was shown to be the most dominant [14]. According to another study, it is essential to understand how force acts on the soot particles in order to determine the soot movements [15]. The forces that acts on the soot particles are drag, electrostatic, gravitational, acoustic, diffusiophoretic and thermophoretic [15][16].

The objective of this study is to analyze soot movement 8° crank angle ATDC in a cylinder of a diesel engine under the influence of drag force and to predict the possibility of soot particles to stick to the wall of the cylinders.

Kiva-3v, and Mesh Configuration

Kiva-3v was used in previous investigation to obtain data of in-cylinder soot formation. The data that were obtained from the Kiva-3v simulation were velocity vectors of the soot, fuel, temperature, pressure and others [6]. It employed a two step model: Hiroyasu's soot formation [11] and Nagle and Strickland-Constable soot oxidation [12] rate expressions.

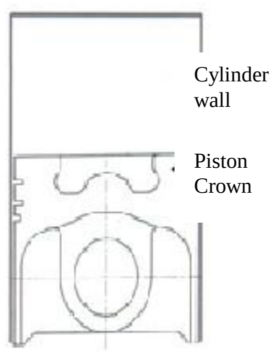

Fig. 1: Crown piston Configuration

Table 1: Specifications of the Engine

Parameters	Specifications
Engine Type	4 valve DI diesel
Bore × Stroke	86.0 × 86.0 mm
Squish height	1.297140330 mm
Compression Ratio	18.2:1
Displacement	500 cm^3
Piston Geometry	Bowl-in-piston

Specifications of Engine. The engine has a bowl-in-piston and flat cylinder head face configuration, with a seven-hole injector installed vertically and centrally. The schematic diagram for crown piston configuration is shown in Figure 1. The simulations were carried out for the combustion system of a 4 valve DI diesel engine from inlet valve closing (IVC) to exhaust valve opening (EVO). The specifications of the engine are bore × stroke: 86.0 × 86.0 mm, squish height: 1.297140330 mm, compression ratio: 18.2:1 and displacement: 500 cm^3, speed: 2500rpm. The details of the specification of engine and mesh specification are shown in Table 1 and Table 2 [6].

Table 2: Specifications of the mesh configuration

Parameters		Mesh configuration
Total number of cells		201,900
Number of cells	Azimuthal	150
	Radial	37 (20 in bowl region)
	Axial	39 (15 in bowl region)
Resolution	Azimuthal (°)	2.4°
	Radial (mm)	0.83 – 1.15
	Axial (mm)	0.99 – 3.63

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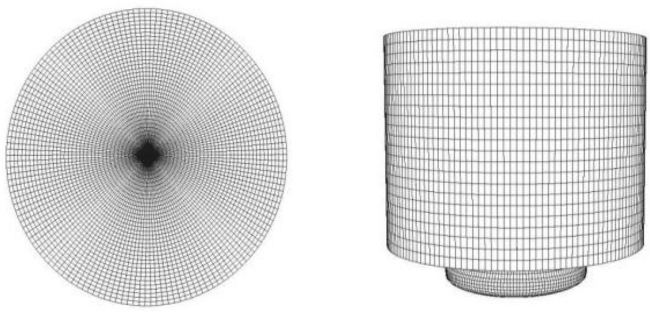
Figure 2 shows the top and side view of the mesh configuration of the piston. The data from experimental result by [7] was used for the simulation and was used for model validation.



Top view Side view

Fig. 2: Mesh configuration of piston bowl-in

Soot Particle Tracking. By using MATLAB, the data for soot concentration that was used by Mahmood [6] was employed to investigate the soot movement in the combustion chamber. The mathematicals algorithm which was used in the MATLAB routine are trilinear interpolation and 4th order Runge-Kutta. In this study, the drag force equation is included in the simulation to determine soot movement. The drag force equation is

$$F_d = \frac{1}{2}\rho v^2 C_d A \quad (1)$$

F_d is the force of drag, ρ is the density of the fluid, v is the velocity of the object relative to the fluid, A is the area and C_d is the drag coefficient.

To analyze the movement of the soot particles, it is necessary to identify the initial position of the soot particle. This can be found based on the zone of soot distribution with certain crank angle ATDC [6]. After selecting the crank angle and zone, the starting coordinate in radial (rho), angular (θ) and axial direction (z) were also decided. Soot particle movement paths have been studied by considering reasonable crank angle .In present paper the reasonable crank angle that is investigated in is at 8° ATDC. 8° ATDC is at the intermediate duration of fuel injection which contains soot. A comparison of the soot particle influenced by drag force and without drag force was carried out from the results of the simulation.

Results and Discussions

With Drag Force	Without Drag Force

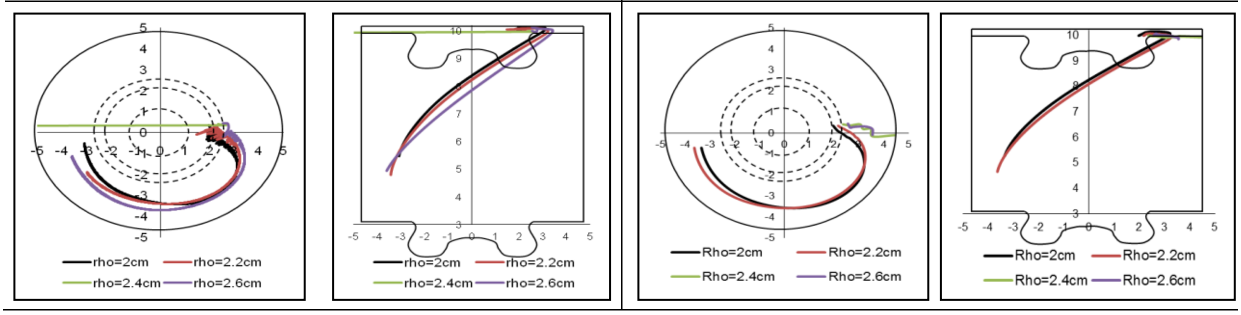


Fig. 3: Radial sensitivity: Rho: 2.0-2.6cm, θ=10º and z=10cm of soot particle movement from 8° ATDC to 120° ATDC

By considering the Radial sensitivity, rho: 2.0-2.6cm, angular (θ): 10º and axial direction (z): 10cm, the soot movement path from 8° ATDC to 120° ATDC was shown in Figure 3. The results shows that when the piston moves downward, almost all the soot particles move downwards and moves towards the cylinder wall. The combination of swirl, squish and reverse squish were the reason the soot particle moves towards the cylinder wall.

The result of soot particle movement influenced by drag force shows that at rho=2cm, the soot particle movement moves nearer to the cylinder wall. Comparing the movement of soot particle influenced by drag force and without drag force shows that the movement is considerably similar. The movement of soot near to the cylinder wall will cause contamination to the lubricant oil. Therefore it is suggested to modify the design of piston or fuel spray injector angle.

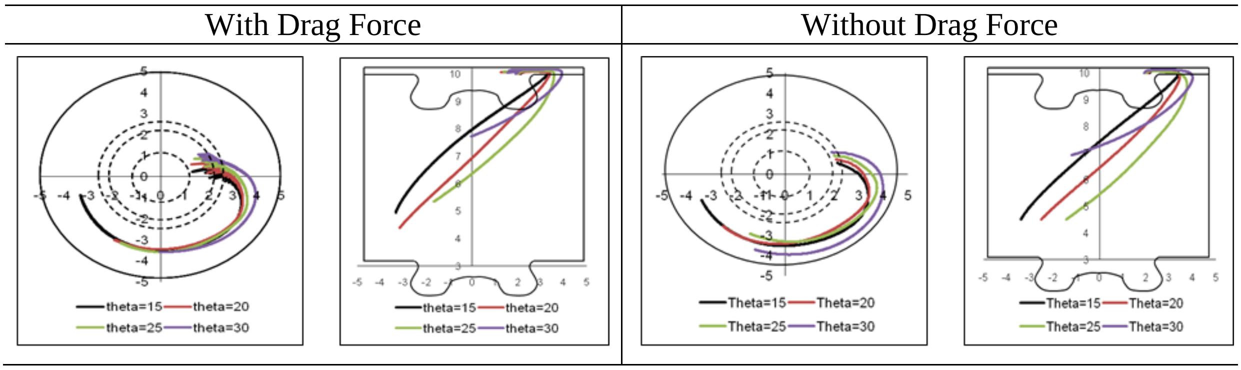


Fig. 4 Angular sensitivity: rho= 2.3 cm, θ =15°-30°, z=10cm of soot particle movement from 8° ATDC to 120° ATDC

Analyses of the soot particle movement by considering the sensitivity of angular were also carried out. Figure 4 shows the Angular sensitivity: radial distance= 2.3 cm, θ =15°-30°, z=10cm). The soot particles move downwards in and anti-clockwise motion.

In this zone, the angular sensitivity has very little influence on the soot particle movement as the comparison between movements of soot particle influenced by drag force and without drag force showed very similar result. The influence of drag force causes the movement path to become shorter compared to the soot particle movement without drag force.

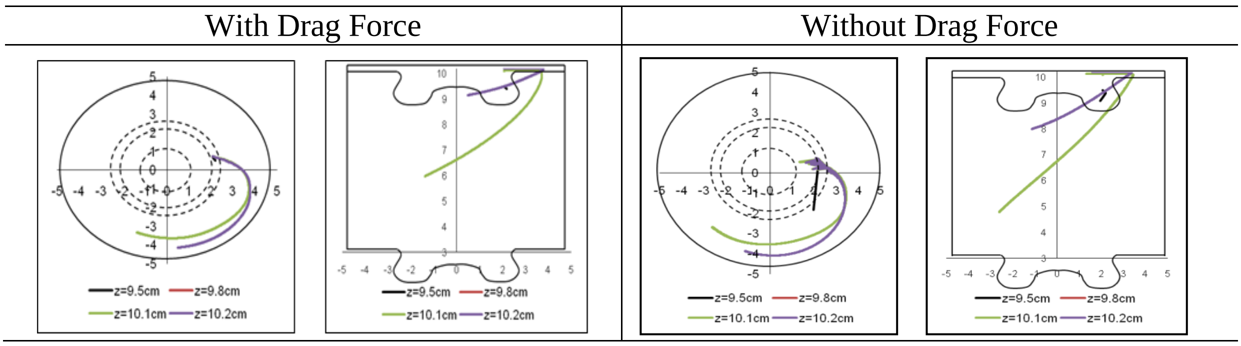


Fig. 5: Axial sensitivity: rho= 2.3 cm, θ =20°, z=9.5-10.2cm of soot particle movement from 8° ATDC to 120° ATDC.

Figure 5 demonstrates the soot particle movement between axial distance= 2.3 cm, θ =20°, z=9.5-10.2cm: of soot particle movement from 8° ATDC to 120° ATDC. At z=10.1 and 10.2, the soot particles moves downward in an anti-clock wise motion.

For z=9.8cm, there is no significant effect towards the soot particle movement path. This is due to the high influence of the velocity of the fuel injection, which causes the soot particle to directly move towards the cylinder wall. As 8° ATDC is the intermediate phase of the fuel injection, therefore the piston moves downwards whereby the motion causes reverse squish and tumble motion to occur.

Besides that, due to the influence of drag force, the soot particle's movement paths become shorter than without the drag force. At the initial position of the soot particle, the movement paths are random but after several angle, the particle moves in a straight line. Figure 5 also shows that when the axial distance increased, the soot movement path will come closer to the cylinder wall.

Conclusion

In order to reduce lubricant oil contamination is by minimizing the transfer of soot particles to the cylinder wall. By understanding the movement path of soot particle in diesel engine, measures to reduce soot particle movement towards the cylinder wall can be identified.

Soot particle movement in a diesel engine depends on the starting point in radial, angular and axial. Most of the soot particles at 8° ATDC move downwards in and anti-clockwise motion approaching the cylinder wall. Hence, the soot particles from these points are likely to give high risk to lubricant oil contamination problem. The modification of the bowl, piston shape and spray angle is expected to reduce the possibilities of the soot particle moving towards the cylinder wall. This will be investigated further in the future. Drag force plays a big influence on the movement of the soot particle. The path of the soot particle becomes shorter than that of without drag force.

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