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Effects of Split-Main Injection Ratios on Diesel Combustion and Soot Emission Performance

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Abstract. In this study, three-dimensional simulations are performed to determine the effects of split-main injection ratios on the soot formation process in a single-cylinder, light-duty, direct-injection diesel engine. Here, a multi-component diesel surrogate model is used to represent the actual diesel fuel and the effects of variations in fuel injection ratios, such as single-injection scheme, split-main injection scheme with ratios of 75-25, and 60-40, on the diesel combustion and soot formation predictions are investigated. It is found out that the use of split-main injection ratio of 60-40 is able to achieve the lowest soot emissions as compared to the others owing to its higher soot oxidation rate.

1. Introduction

Diesel engines is one of the powertrains that is widely used in road transportations, due to its higher thermal efficiency as compared to other thermal propulsion engines. However, it is noted that the fuel combustion events in diesel engines produce particulate emissions which are harmful to the environment during their operations. Consequently, stringent emissions regulations, such as the EURO emissions standards [1], are being implemented to limit the emissions of engines in order to protect the environment. Hence, developments of more efficient engines as well as cleaner fuels are essential.

Over the years, several strategies such as advanced after-treatment devices, injection rate-shaping, and exhaust gas recirculation had been introduced with various degrees of improvement in reducing the exhaust emissions of diesel engines. However, much focus is now positioned in controlling the in-cylinder combustion and soot formation process as these existing technologies inching towards their limits [2]. Several fuel injection strategies are proven to be effective in reducing soot formation and gases emissions such as variations in injection pressure and multiple injection scheme. There are various combinations of multiple injection strategies. For instance, pilot-main injection strategies, main-post injection strategies, etc. Pilot injection can help in reducing NO_x emissions and particulate matter emission, whereas immediate post injection aids in soot oxidation [3,4]. Here, focus is paid on investigation of split-main injection parameters. It is noted that experimental approach to elucidate these are highly complex, laborious, and expensive. In view of this, this study aims to investigate the effects of variations in split-main injection ratio on soot emission performance in a single-cylinder, light-duty, direct-injection (DI) diesel engine using Computational Fluid Dynamics (CFD) approach.

2. Numerical Configurations

In this study, the numerical simulations are performed using the ANSYS FLUENT software. Here, a multi-component kinetic model, namely MCDS2, is selected as the surrogate model to emulate the combustion behaviours of an actual diesel fuel (i.e. Diesel Fuel No. 2) in a DI diesel engine. The

MCDS2 consists of four different fuel components, such as n-hexadecane (HXN, straight-alkane), 2,2,4,4,6,8,8-heptamethylnonane (HMN, branched-alkane), cyclohexane (CHX, cyclo-alkane) and toluene (aromatics). The respective fuel compositions are HXN : HMN : CHX : Toluene = 42% : 20% : 10% : 28% by mass. Further details of the surrogate model can be found in the previous study [5].
On the other hand, a 60º sector mesh, as shown in Figure 1, is employed in this study to represent 1/6 of the combustion chamber as the injection nozzle is equally-spaced with six injector holes.

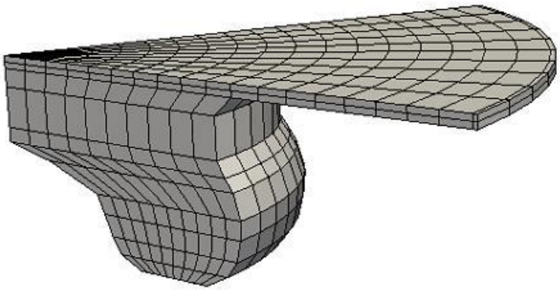

Figure 1. Sector mesh of the combustion chamber.

Besides, the specifications of the test engine along with the corresponding operating conditions are detailed in [6]. The key numerical settings employed in the study are depicted in Table 1. It is important to highlight that the computational grids as well as the numerical setups are determined through appropriate parameter studies.

Table 1. Numerical settings applied in the simulations.

Droplet breakup model	KH-RT (B_1 = 30, C_L = 15)
Turbulence model	RNG k-epsilon (C_1=1.52)
Soot formation model	Moss-Brookes Model

3. Combustion Characteristics

In this section, the fuel combustions using single-injection, 60-40 and 75-25 split-main injection schemes are simulated. Then the computed pressure and heat release rate (HRR) curves are compared with the experimental measurements, as demonstrated in Figure 1. Here, the HRR for all the injection profiles are calculated by using the following equation:

$$\frac{dQ}{dt} = \frac{\gamma}{\gamma-1} p \frac{dV}{dt} + \frac{1}{\gamma-1} V \frac{dp}{dt} \quad \text{Equation (1)}$$

where, t is the time, p and V represent the cylinder pressure and volume respectively. The constant γ is the ratio of specific heat, which is set as 1.35. From Figure 2, it is shown that the pressure and HRR curves predicted by MCDS2 are in reasonably good agreement with the experimental measurements for all three cases.

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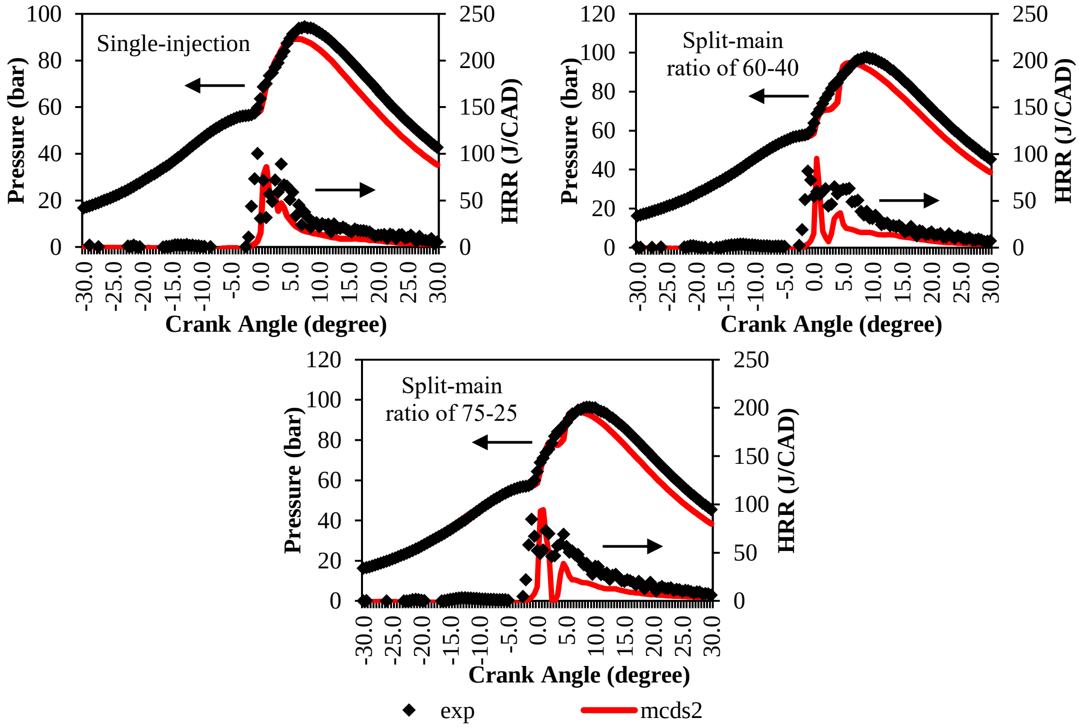

Figure 2. Comparisons of the predicted and measured pressure and HRR curves.

4. In-Cylinder Soot Evolutions

In this section, the predicted soot densities with the applications of single-injection and split-main injection schemes are compared with the experimental soot data at exhaust valve open (EVO) at 131° crank angle (CA) after top dead centre (ATDC). Results are shown in Figure 3. In overall, the computations are seen to be comparable to the values obtained from experiments. It is also observed that the amount of soot generated using the single-injection scheme is the highest among all cases, followed by the 75-25 and 60-40 split-main injection schemes. This can be attributed to greater fuel oxidation rate when split-main injection schemes are used instead of the single-injection scheme. Further analysis is henceforth performed in order to look into these phenomena.

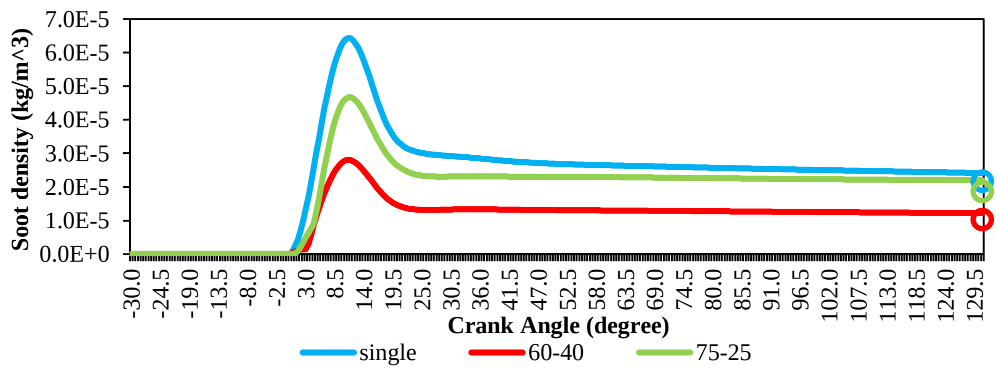

Figure 3. Predicted (–) and measured (○) soot densities using different injection schemes.

Figure 4 illustrates the spatial soot evolutions simulated by MCDS2 using different split-main injection ratios. It is observed that the overall soot production for single-injection case is greater than those using split injection schemes. A significant amount of soot is formed and accumulates at the tip of fuel jet where rich mixtures are present around the piston bowl regions due to continuous replenishment of injected fuel. This observation is consistent for all three cases. In addition, reduction in the total soot concentration is also observed after 12° ATDC due to soot oxidations during expansion stroke.

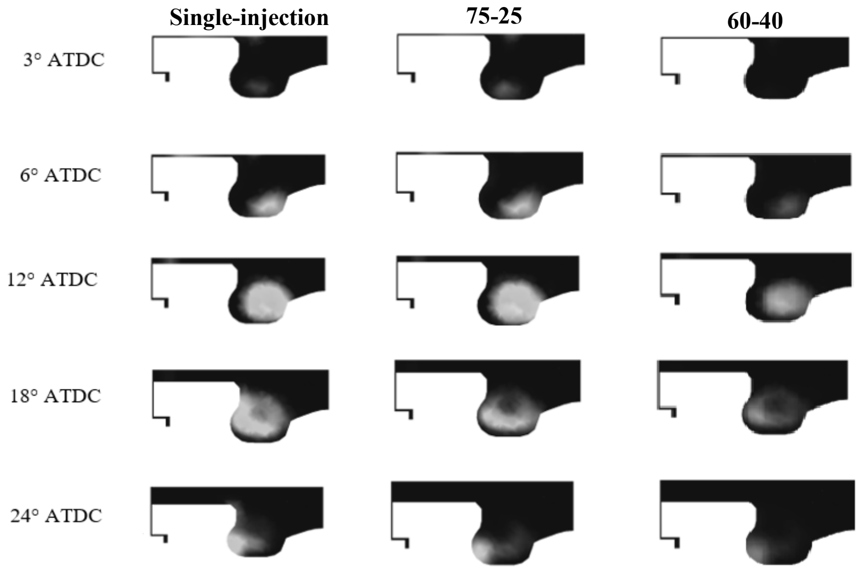

Figure 4. Simulated spatial soot evolutions using different split-main injection ratios.

Furthermore, soot is also found to be most dense at the fuel-rich region. The presence of high amount of soot precursor (i.e. C_6H_6) as well as surface growth species (i.e. C_2H_2) due to the chain-branching and decompositions of fuel components has led to higher soot inception rate at these fuel-rich spots and consequently greater amount of soot is formed. The mass fractions of C_2H_2 for all three cases are presented in Figure 5, along with the mass fractions of O_2 which acts as the soot oxidizing species.

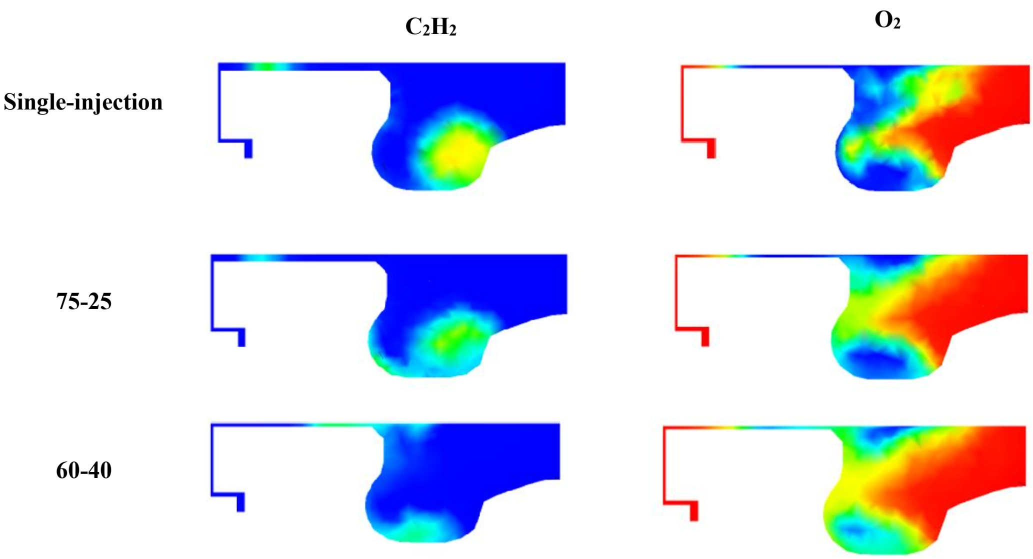

Figure 5. Simulated C_2H_2 and O_2 mass fractions during the combustion events using different split-main injection schemes.

By implementing split-main injection ratios, better air-fuel mixing in the combustion chamber is obtained. With less fuel delivered in the first pulse, there are less fuel-rich regions and initial soot formation can be suppressed. Then, when the second pulse of fuel is delivered, it is able to achieve a more homogeneous mixing due to the turbulence generated by the first pulse of fuel and subsequently reducing the soot formation from the second pulse of fuel. Furthermore, the oxidation is also improved in split-main injection cases. It is mainly attributed to a better distribution and entrainment of oxidizing species due to the turbulence generated by the second pulse of fuel, as shown in Figure 5.

A split-main injection ratio of 60-40 is found to be better at suppressing the overall soot emission as compared to the ratio of 75-25. In the 60-40 split-injection case, the initial soot formation is less because of the smaller amount of fuel injected during the first pulse of fuel injection. Then, there is also no significant rise in the secondary soot formation despite the increase in the amount of secondary injection. This might be due to adequate swirling effects generated by the first pulse of fuel which then promote a homogeneous mixing for the second pulse of fuel. Therefore, there is no significant increment in the secondary soot formation. The oxidation process is also found to be better for 60-40 split-injection. Because the soot formed is less, there are less soot trapped at the centre of soot cloud in which soot oxidation is restrained. With a lower soot formation rate and more effective oxidation, soot emission from 60-40 split-injection cases are lower than that from the 75-25 split-injection.

5. Conclusions

In this work, the effects of split-main injection ratios on the soot emission process are evaluated. The application of 75-25 split-main ratio has seen some reductions in soot formation. It is mainly due to the lesser amount of fuel injected in the first pulse which then leads to lesser soot formation. The soot formation from the second injection is also suppressed because the turbulence induced by the first injection has promoted a better mix between air and the second fuel spray. A lower ratio of 60-40 have resulted in further reduction in soot formation, which is mainly due to lesser soot formation from the first injection. Together with a better soot oxidation, the peak and exhaust soot level are lower as compared to single- as well as 75-25 split injections. From this work, split-main injection scheme with the lowest ratio has the advantage in soot reduction for the current test engine. However, this should be used with caution for other engines with different setup as well as operating conditions.

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