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Theoretical Analysis of the Performance of DI Diesel Engine Operating on Dual Fuel

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Abstract: The present investigation describes the effect of methane addition to diesel fuel in dual fuel mode for direct injection CI diesel engine. The engine was simulated using Computational Fluid Dynamics (CFD) software. The mesh has been generated using “Meshing” code included in the software and combustion process has been analyzed using “Fluent” program. The simulation carried out using neat diesel fuel and dual (0.4 methane/0.6 diesel by mass) mixture at 1500 rpm and full load operation. The total mass fuel was injected to the cylinder in three stages. The simulation outputs such as heat release rate, maximum in-cylinder pressure, maximum in-cylinder temperature and penetration length were used to evaluate the effect of the alternative fuel addition and multiple-injection approach on the combustion process performance. The progress of the combustion process has been monitoring by recording the temperature distribution inside the combustion chamber during the simulation. The results showed that the addition of 0.4 mass fraction of methane to diesel fuel in CI engine gave an increase in the peak in-cylinder pressure, the peak heat release rate, the maximum in cylinder pressure and penetration length compared to neat diesel fuel operation due to higher flame propagation and fast combustion process of methane. Conversely, the methane combustion presented longer auto-ignition delay compared to neat diesel fuel. The simulation results showed good agreement with the experimental outcomes from the literature.

Key words: CI engine, CFD, alternative fuel, engine efficiency, performance, generated, temperature

INTRODUCTION

In general, the alternative fuels such as hydrogen, natural gas and methane when added to IC engines (both gasoline and diesel) improve engines efficiency and decrease emissions. This is due to high heating value, fast combustion characteristic and less emissions production (Szwaja and Grab-Rogalinski, 2009; Antunes *et al*., 2009; Ghazal, 2013a, b). Many researchers have studied the effect of using various alternative gaseous fuels, such as methane, hydrogen, biofuel, ethanol, propane and diethyl ether on the engine performance (37-45). They concluded that, the main disadvantages of the dual fuel combustion are its decrease of brake thermal efficiency and increase of carbon monoxide emissions, compared to neat diesel operation. The pilot fuel quantity accompanied with its injection timing are two important variables, that have a major influence on the performance and pollutant emissions of an engine under dual fuel mode (Papagiannnakis, 2013; Papagiannnakis *et al*., 2007). The hydrogen addition to diesel fuel increase the homogeneity of the mixture results in improving combustion efficiency. Conversely, the hydrogen enrichment diesel increases auto-ignition delay, high self-ignition temperature compared to neat diesel fuel in-cylinder pressure and temperature and peak heat release rate results in combustion knock and NO_x increment (Szwaja and Grab-Rogalinski, 2009; Ghazal, 2013a, b). The use of natural gas addition to the conventional diesel fuel in dual mode has been proved as an effective approach for improving the Soot/NOx trade-off while decreasing the thermal efficiency compared to neat diesel operation (Papagiannnakis and Hountalas, 2003, 2004). Moreover, natural gas is suitable for diesel engines with relatively high compression ratio because of his high octane number. In addition, it mixes uniformly with air, resulting in increased engine performance and decreased pollutions (50-57). (Papagiannakis, 2013) studied the effect of air inlet preheating and exhausts gas recirculation on the performance and exhaust emissions of a pilot ignited dual fuel diesel engine. He concluded that the increase of both parameters improve engine efficiency and reduce CO emissions from a pilot ignited dual fuel diesel engine, without imparting any serious problem to engine operational lifetime. The mixture of hydrogen-natural gas fuel has been studied by many researchers (Ghazal, 2013a, b; Raman *et al*., 1996, Nagalingam *et al*., 1983; Das, 1996). Dulger and Swain investigated an 80% CNG and 20% H_2 mixture burning SI engine numerically (Boretti, 2011a, b). They showed that when methane-hydrogen mixture is compared to pure methane operation with same equivalence ratios, methane and hydrogen mixture increased brake thermal efficiency and NOx emissions while decreasing unburned HC and CO. The effect of hydrogen amount added to methane on the engine performance has been investigated by Ghazal (2013a, b). The analysis of the results shows that the addition of some hydrogen to methane between 0.4 and 0.6 H_2 with equivalence ratio near to stoichiometric and engine speed between 2000 and 3000 rpm produces notable improvements to engine performance and emissions. One of the techniques to avoid high in cylinder temperature and pressure is using the multiple-stage injection strategy which generates a mixture by the combination of an early injection and late injection aTDC. The system controls the first injection timing, quantity, temperature and pressure to prevent any high burning temperature and then delivers a second and third injection to initiate the high temperature reaction a TDC. Delaying the combustion phase near to TDC generally leads to a higher power compared to PCCI combustion due to reduced negative work (Akagawa *et al*., 1999; Kook and Bae, 2004).

In this research, the effect of methane addition to diesel fuel in dual mode for direct injection CI engine with triple-injection approach have been investigated. The simulation has been conducted using professional "Fluent" code to control the combustion process inside the engine. The output parameters: in-cylinder temperature and pressure, turbulent kinetic energy, penetration length and heat release rate have been used to show the effect of the alternative fuel addition on the CI diesel engine. The results have been fully discussed and compared with the experimental data from the literature.

MATERIALS AND METHODS

Simulation model: In this study, an analytical model of four stroke direct injection diesel engine has been built using CFD Software to account the effect of the methane addition to diesel fuel. The simulation started from the intake valve close angle to exhaust valve open angle. After intake valve closure and during the whole course of combustion and expansion, detailed chemical reaction kinetics was considered for the resulting mixture. This model could predict in detail, the consequent temporal changes to the concentrations and properties of the contents of the cylinder and the associated energy release rate. The main engine parameters are illustrated in Table 1. The chemical and thermal data for combustion process are included in the CFD database. The program employs pressure based solver and diesel unsteady flamelet model. The turbulence model used in the simulation is RNG k-epsilon model. The fuel used in the simulation is a neat diesel fuel and a dual fuel (0.4 CH_4/ 0.6 diesel) injected by pulsed injector with 70° injection angle. The engine speed 1500 rpm is kept constant. The methane specifications are presented in Table 2. The simulation boundary conditions and initial conditions are illustrated in Table 3 and 4, respectively. The geometry mesh is illustrated in Fig 1. The total fuel injected mass was injected into combustion chamber in three steps and it is presented in Fig. 2. The program enables monitoring the temperature distribution during the whole simulation. The output parameters for the analysis: in-cylinder pressure in-cylinder temperature, heat transfer rate and penetration length are recorded in tables and figures. The effect of methane addition to diesel fuel on the engine performance has been fully discussed.

Table 1: Engine parameters

Paramenters	Values
Bore	90 mm
Stroke	110 mm
Connecting rod length	170 mm
Compression ratio	16
Crank radius	60 mm
Fuel injection duration	26°CA
IVC	40° aBDC
EVO	70° bBDC
Initial temperature	400 (K)
Initial pressure	3.4 (atm)

Table 2: Methane specifications (Karim, 2003)

Paramenters	Values
Density (kg/L)	0.00071
Higher heating value (kJ/kg)	52,680
Lower heating value (kJ/kg)	46,720
Molecular mass (kg/kmol)	16.04
Air/fuel ratio (weight)	17.2
Auto-ignition temperature (K)	813
Laminar flame speed (m/sec)	0.38
Flammability limits (% by volume)	5.3-15.0

Table 3: Boundary conditions

Paramenters	Values
Cylinder wall temperature	440 (K)
Cylinder head temperature	480 (K)
Piston surface temperature	560 (K)

Table 4: Initial condition

Paramenters	Values
Pressure	3.5 (bar)
Temperature	400 (K)
Turbulent kinetic energy	10,000 (cm^2/sec^2)
Dissipation rate	10,000 (cm^2/sec^3)
Initial engine swirl ratio	1.4

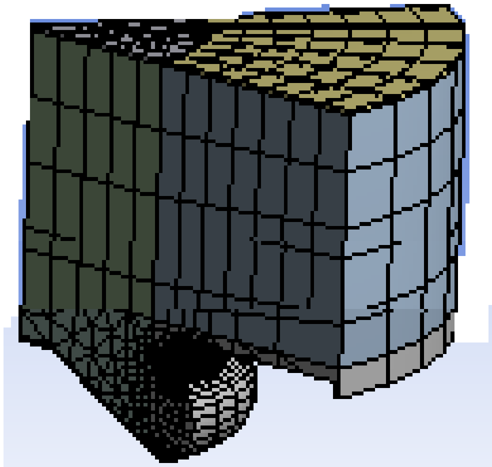

Fig. 1: Meshing geometry

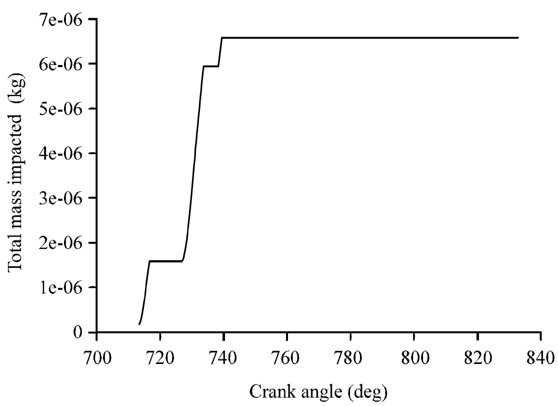

Fig. 2: Total mass injected versus crank angle

RESULTS AND DISCUSSION

Figure 3 and 4 show the maximum in-cylinder temperature and in-cylinder average temperature versus engine crank angle for both cases (neat diesel fuel and dual methane/diesel fuel). They show an increasing of the combustion temperature when methane is added to diesel fuel compared to neat diesel. A minor drop in temperature before the start of combustion is observed in both cases which is due to the vaporization of the fuel. A sharp rise in temperature during the combustion is observed in the case of the neat diesel fuel as compared to the case for dual fuel (Selim, 2001).

Figure 5 and 6 present the maximum static pressure and the volume average static pressure inside combustion chamber versus crank angle for neat diesel and methane/diesel dual fuel. They show an increase of the maximum combustion pressure for methane/diesel fuelling than the neat diesel fuelling level (Mansour *et al.*, 2001).

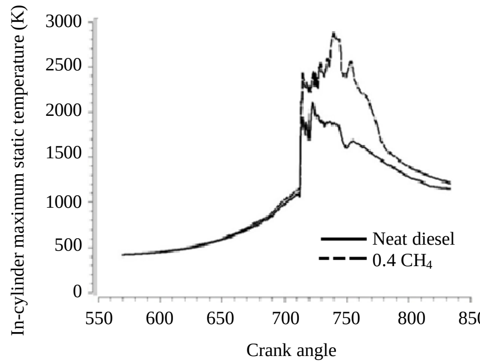

Fig. 3: Maximum in-cylinder temperature versus crank angle

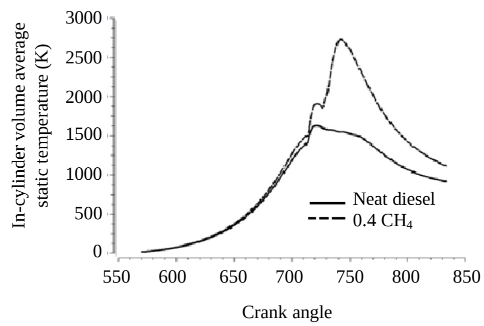

Fig. 4: Volume average static temperature versus crank angle

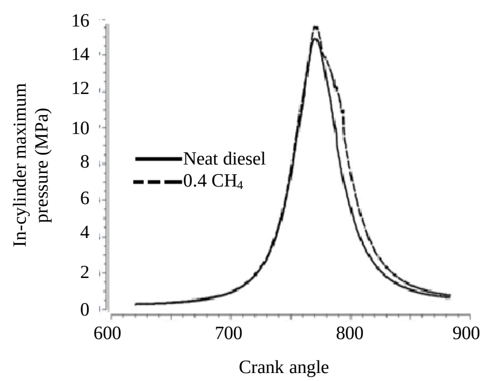

Fig. 5: Maximum in-cylinder pressure versus crank angle

For the dual-fuel engine, the maximum pressure is always higher than in the diesel fuel case due to the combustion and extra heat released from gaseous fuels (Selim, 2001). Moreover, the addition of gaseous fuels increases peak pressure due to higher energy release during their combustion. The higher air velocity and gaseous-air entrainment due to turbulence motion in the combustion chamber lead to increase in rate of evaporation of the liquid fuel and gives higher rate of heat release resulting in higher peak pressure in the cylinder (Selim, 2001). In addition, Sharper peaks are observed for dual fuel combustion compared to neat diesel fuel (Henham and Makkar, 1998). In general, the maximum combustion pressure for gaseous fuelling is slightly higher for all engine speeds than the diesel fuelling level. The general trend is governed by decreasing pressure and temperature levels with increasing speeds (Mansour *et al*., 2001).

Figure 7 show the heat release rate inside the combustion chamber. It shows that for methane/diesel dual fuel the heat release rate is retarded than neat diesel

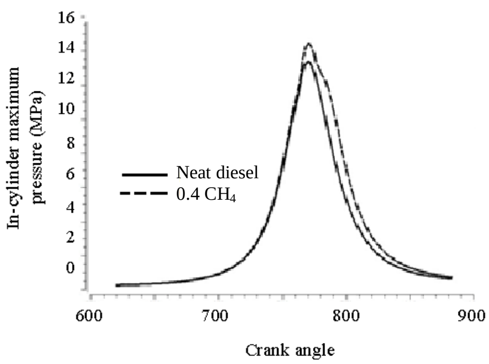

Fig. 6: Volume average static pressure versus crank angle

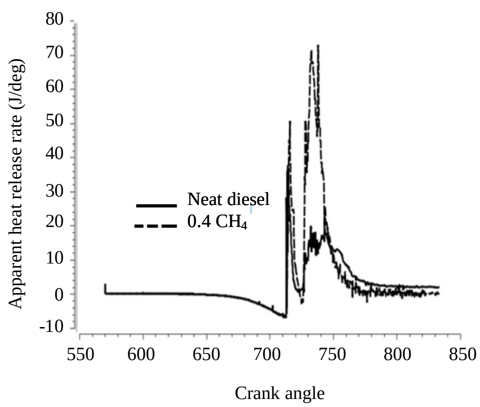

Fig. 7: Heat release rate versus crank angle

due to the decrease of the combustion rate under dual fuel operation during the premixed controlled combustion compared to the one under normal Diesel operation (Papagiannakis and Hountalas, 2004). Moreover, the heat release rate is increased with dual fuel compared to neat diesel. Observing the total heat release curves in Fig. 7, during the second phase of combustion (diffusion combustion), it is revealed that the total rate of heat release under dual fuel operation is obviously higher compared to the one under normal diesel operation. The effect is stronger at low engine speed, revealing later combustion of the gaseous fuel (Papagiannakis and Hountalas, 2004). In addition, the ignition delay period which is defined as the time from fuel injection to start of heat release increased slightly with the addition of methane (White *et al*., 2006). This may be because the addition of methane in the charge reduces the air intake and hence oxygen in the cylinder (White *et al*., 2006). Another reason may be due to the high ignition temperature of methane and higher start of combustion time. At higher concentration of hydrogen in the mixture, ignition delay decreases due to addition of significant amounts of energy and species (Borreti, 2011). Figure 7 shows the heat release rate versus crank angle for both cases. The heat release rate of neat diesel fuel by first phase of combustion is 37 (J/deg) and for dual fuel 50 (J/deg). It shows two phases of combustion for neat diesel. The first phase is due to premixed combustion while second phase by diffused combustion of diesel fuel. In dual fuel operation, heat release is mainly due to three phases of combustion, first by premixed burning of pilot diesel. In the second phase of combustion, it is due to auto ignition of gaseous-air mixture in the close vicinity of pilot spray zone and diffusive burning of remaining pilot diesel fuel. In the third phase of combustion, heat is released by flame propagation from spray zone into the gaseous fuel-air mixture (Poonia *et al*., 1998).

The same results are shown in the Fig. 8. It presents the combustion initiation and duration time for both cases. We can note that, the ignition of the combustion

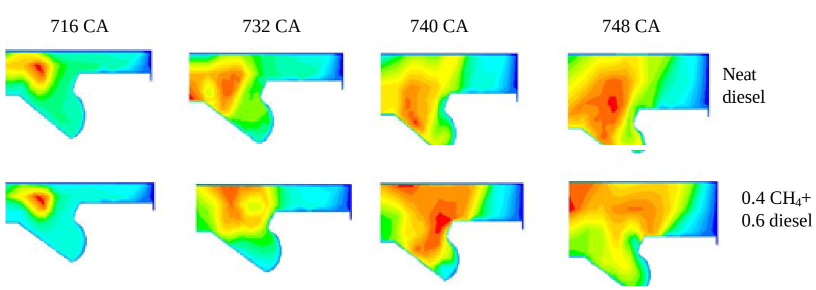

Fig. 8: The temperature distribution versus crank angle

process for neat diesel fuel is faster than for dual fuel. In addition, the combustion duration is higher under dual fuel operation at the first phase of combustion. For the second phase of combustion the difference is reduced and combustion duration under dual fuel operation becomes lower compared to normal diesel operation. This is properly due to high flame speed for methane. The same results have been obtained by Papagiannakis and Hountalas (2004). He concluded that, "the duration of combustion at low engine speed under dual fuel operation is longer compared to high engine speed where the engine is warmer, having a positive effect on the combustion of the gaseous fuel (lower ignition delay and faster flame speed" (Papagiannakis and Hountalas, 2004). This will increase combustion process efficiency. Moreover, at low load, the combustion duration under dual fuel operation is longer compared to normal diesel operation while at high load, it is shorter (Papagiannakis and Hountalas, 2004).

CONCLUSION

In the present research an analytical study has been carried out to examine the effect of dual fuel (methane/diesel) combustion on the performance of direct injection compression ignition engine. The analysis data show that, using dual fuel combustion mode will increase ignition delay and retard heat release rate but decrease combustion duration and enhance combustion efficiency compared to neat diesel fuel mode under the same operation conditions.

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