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Combustion Simulation of Direct Injection CI Engine Operating on Dual Fuel Using CFD

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In general, the alternative fuels such as hydrogen and methane when added to internal combustion engine improve efficiency and decrease emissions. This is due to improving homogeneity of the mixture, high heating value, fast flame propagation, and less emissions. Conversely, the hydrogen has high self-ignition temperature compared to neat diesel fuel, high in-cylinder pressure and temperature, and peak heat release rate results in combustion knock. The present investigation describes the effect of hydrogen and methane addition to diesel fuel in dual mode for direct injection CI engine with multi-stages fuel injection mode. The intermittent strategy has been adopted in the simulation to avoid difficulties associated with abnormal combustion inside the combustion chamber and to reduce the amount of NO and soot exhausted from diesel engines. A single cylinder 4- strokes engine has been simulated using computational fluid dynamics FLUENT code. The simulation carried out for three testing fuels: neat diesel fuel, dual hydrogen–diesel, and dual methane–diesel. The total mixture of fuel mass was injected in three stages. The engine speed is 1500 rpm and run at full load. The simulation outputs such as heat release rate, in-cylinder pressure, in-cylinder temperature, were used to evaluate the effect of the alternative fuel addition on the engine performance. The results showed that the addition of a certain amount of gaseous fuel to diesel fuel in CI engine gave a significant increase in the peak in-cylinder pressure, and heat release rate compared to neat diesel fuel operation results in increase of engine efficiency and decrease of pollution.

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PACS/topics: methane, hydrogen, CI engine, combustion, efficiency, CFD

1. Introduction

One of the major challenges for automobile makers in the recent years is the reduction of the emissions during the engine operation or road vehicles to minimize the human and environment hazardous associated with these emissions. Many solutions have been proposed to increase the engine efficiency and decrease emissions including gaseous fuel engine and hybrid cars. The gaseous fuels such as methane, hydrogen, and natural gas improve overall engine performance and decrease emissions due to faster combustion and less carbon content in the fuel [1–3]. In addition, the effect of alternative fuels as ethanol, biofuel, and diethyl ether when added to diesel fuel has been performed by several research papers [4–10]. The results showed that compression ignition (CI) engine when operating on duel fuel (mixture of diesel fuel with alternative fuel) has lower thermal efficiency and higher carbon monoxide emissions compared to CI engine operating on diesel fuel. Several factors have effect on duel fuel engine performance such as the amount of diesel fuel injected to the combustion chamber, the injection timing, and the pressure and temperature of injected fuel [11, 12]. The hydrogen addition to diesel fuel improves homogeneity of the mixture, increases heating value, accelerates the flame propagation, and decreases emissions. Conversely, the hydrogen has high self-ignition temperature compared to neat diesel fuel, high in-cylinder pressure and temperature and peak heat release rate resulting in combustion knock, NOx increment and shorter engine life [3, 13]. The addition of natural gas to diesel fuel has been confirmed by many researches [14–16]. They concluded that the combustion of the mixture of natural gas and diesel fuel will improve engine efficiency, reduce emissions, and improve the soot/NOx trade-off [17–24]. The mixture of hydrogen–methane fuel and hydrogen–natural gas mixture for CI engine has been studied by many researchers [1, 4, 25, 26].

The effect of hydrogen amount added to methane on the engine performance has been investigated by [1]. The analysis of the results shows that the addition of some hydrogen to methane in certain amount with stoichiometric equivalence ratio and engine medium speed produces notable improvements to engine performance and emissions. Boretti [2] and Gomes et al. [6] investigated an 80% CNG and 20% H_2 mixture burning CI engine numerically. They found that the performance of CI engine operating on methane–hydrogen mixture is compared to pure methane with the same equivalence ratios increase brake thermal efficiency and NOx emissions while decrease unburned HC and CO. One of the techniques to avoid high raising 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 results in a combustion process near to TDC which leads to a higher power compared to PCCI combustion due to reduced negative work [27].

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In this work, the effect of the mixture of methane–diesel fuel and hydrogen–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 such as cylinder temperature and pressure, turbulent kinetic energy, and heat release rate have been used to show the effect of the alternative fuel addition on the CI diesel engine.

2. Simulation model

A simulation model has been built using the professional FLUENT computational fluid dynamics (CFD) code. The 3D model used to investigate the direct injection compression engine operating on neat diesel fuel, methane–diesel mixture, and hydrogen–diesel mixture. This model predicts the details of the consequent temporal changes to the concentrations and properties of the contents of the cylinder and the associated energy release rate. Each simulation run starts from the closing angle of the intake valve to the opening angle of the exhaust valve. The main engine parameters are illustrated in Table I. 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 k–ε model. The fuel used in the simulation is a neat diesel fuel, mixture fuel (0.4 CH_4/0.6 diesel), and mixture (0.4 H_2/0.6 diesel). The engine speed 1500 rpm is kept constant. The methane, hydrogen and diesel specifications are presented in Table II. The simulation boundary conditions and initial conditions are illustrated in Table III. The mesh geometry is presented in Fig. 1. The mesh has been generated using CFD mesh included in the software to gain the most optimized values of the engine parameters with high accuracy. The total fuel mass was injected directly to the cylinder in three steps as shown in Fig. 2. The program enables monitoring the temperature distribution during the whole simulation. The output parameters for the analysis: pressure, temperature, and heat transfer rate are recorded in the simulation CFD-post for further analysis. The effect of methane and hydrogen addition to diesel fuel on the engine performance has been fully discussed.

TABLE I

Engine parameters

bore	95 mm
stroke	105 mm
connecting rod length	165 mm
compression ratio	17.5
fuel injection duration	26° CA
IVC	43° aBDC
EVO	72° bBDC
initial temperature	400 K
initial pressure	3.5 atm

TABLE II

Fuels specifications

Property	Methane	Hydrogen	Diesel
density [kg/dm^3]	0.00071	0.0000898	0.84
higher heating value [kJ/kg]	52,680	141,000	52000
lower heating value [kJ/kg]	46,720	120,000	42700
molecular mass [kg/kmol]	16.04	2	170
air/fuel ratio (weight)	17.2	34	14.7
auto-ignition temperature [K]	813	858	588
laminar flame speed [m/s]	0.38	2.93	0.087
flammability limits [vol.%]	5.3-15.0	4-75	1-6

TABLE III

Initial conditions

pressure	3.5 bar
temperature	400 K
turbulent kinetic energy	10,000 cm^2/s^2
dissipation rate	10,000 cm^2/s^3
initial engine swirl ratio	1.4
cylinder wall temperature	440 K
cylinder head temperature	480 K
piston surface temperature	560 K

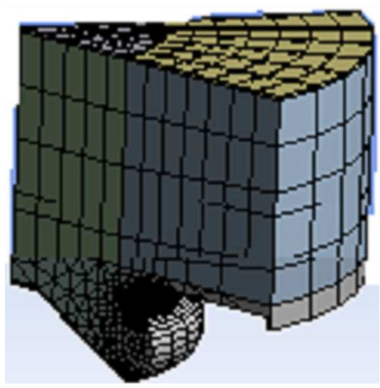

Fig. 1. Meshing geometry.

3. Mesh generation

For the present simulation a 3D geometrical model of a single cylinder engine has been built. Due to the complexity of the computational domain it was divided into sub-volumes to simplify the meshing process. The program used finite volume method with structured mesh and tetrahedral cells. The boundary conditions used in the simulation are inlet pressure and outlet pressure at the intake and exhaust ports. The geometry walls were treated as an adiabatic.

4. Results and discussion

Figure 3 shows the effect of heat release for different fuels. It performs that when hydrogen added to

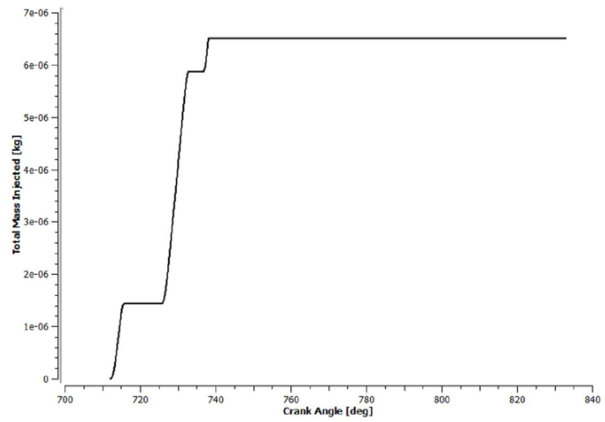

Fig. 2. Total mass injected versus crank angle.

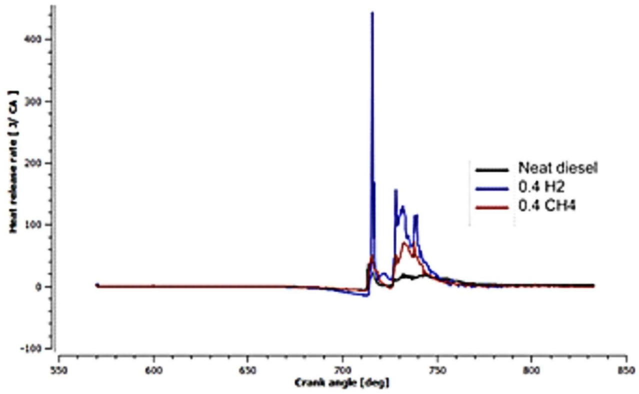

Fig. 3. The effect of different fuels on heat release rate.

diesel the mixture presents high heat release speed due to fast hydrogen combustion. The main drawback for using a large amount of hydrogen in the mixture is the ability of denotation combustion and resulting in knock phoneme inside the cylinder which causes the engine damage. In addition, the heat release starts in advance phase than other fuels.

Figures 4 and 5 present the pressure and temperature inside the engine. As shown in Fig. 4 the maximum pressure occurs when using hydrogen–diesel mixture.

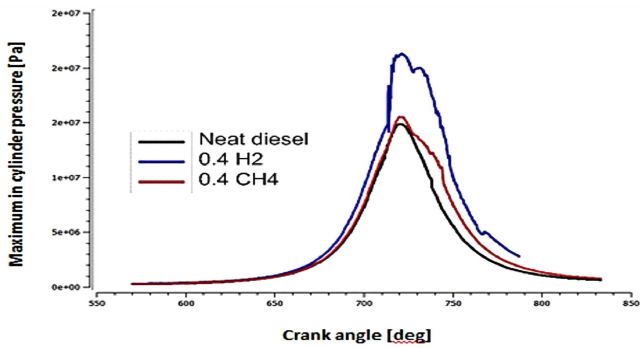

Fig. 4. The effect of different fuels on cylinder pressure.

This is due to the high heating value for the hydrogen fuel compared with other fuel mixtures. Moreover, the combustion process starts earlier for hydrogen–diesel mixture as shown in Fig. 5.

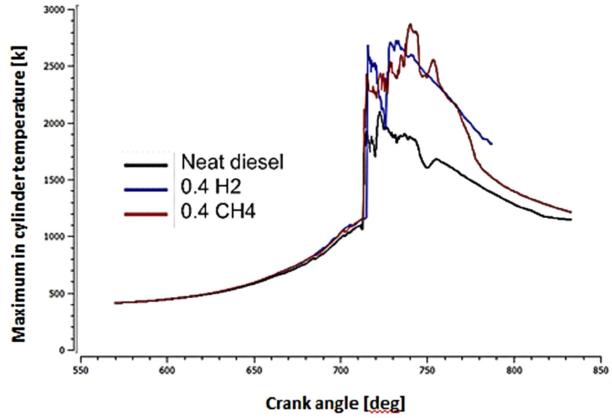

Fig. 5. The effect of different fuels on cylinder temperature.

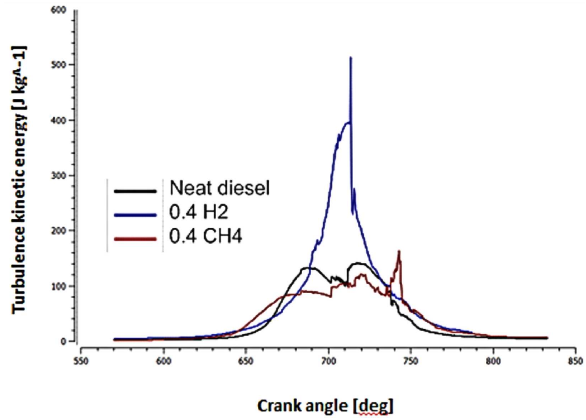

Fig. 6. The effect of different fuels on turbulence kinetic energy.

Figure 6 shows the effect of turbulence kinetic energy for different fuels and crank angle phases. As shown in the figure the hydrogen–diesel mixture has the highest kinetic energy as expected. This is due to high combustion temperature and high velocity fluctuations inside the engine Reynolds–averaged Navier–Stokes equations which are solved by FLUENT code. The temperature distribution inside the engine is presented in Fig. 7. It confirms that as hydrogen mix with diesel fuel the hot regions are extended beyond the expansion stroke resulting in high temperature of exhaust gases.

5. Conclusion

The results showed that the addition of 0.4 mass fraction of hydrogen to diesel fuel in CI engine gave a significant increase in the peak in-cylinder pressure and the

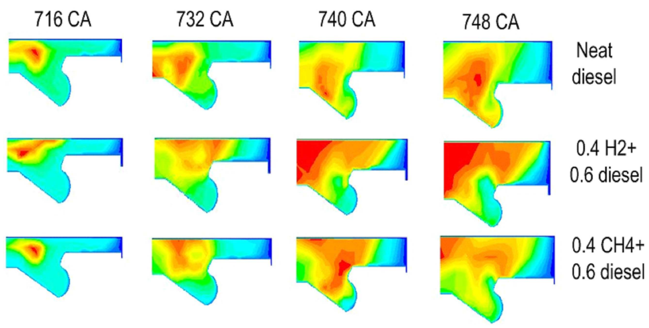

Fig. 7. Temperature distribution for different crank angle and different fuels.

peak heat release rate compared to neat diesel fuel operation due to the high flame propagation and fast combustion process of hydrogen which results in increase of overall engine performance. Conversely, the hydrogen combustion presented long auto-ignition delay and high self-ignition temperature compared to neat diesel fuel.

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