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ORIGINAL ARTICLE

Effect of replacing nitrogen with helium on a closed cycle diesel engine performance

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KEYWORDS

Engine simulation;
CFD;
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Abstract One of most important problems of closed cycle diesel engine is deterioration of cylinder pressure and consequently the engine power. Therefore this research aimed to establish a multi zone model using Computational Fluid Dynamic (CFD) code; ANSYS Fluent 14.0 to enhance the closed cycle diesel engine performance. The present work investigates the effect of replacing nitrogen gas with helium gas in different concentration under different engine load and equivalence ratios. The numerical model results were validated with comparing them with those obtained from the previous experimental results. The engine which was used for the simulation analysis and the previous experimental work was a single cylinder with a displacement volume of 825 cm^3, compression ratio of 17 and run at constant speed of 1500 RPM. The numerical results showed that replacing nitrogen with helium resulted in increasing the in-cylinder pressure. The results showed also that a percentage of 0.5–10% of helium on mass basis is sufficient in the recovery needed to overcome the drop in-cylinder pressure and hence power due to the existence of CO_2 in the recycled gas up to 25%. When the CO_2 % reaches 25%, it is required to use at least 10% of He as replacement gas to achieve the required recovery.

1. Introduction

Over a few decades a diesel engine has proven to be one of the most effective energy conversion systems. It is widely used as a power source of stationary power plants, military and commercial marine vessels [1–3]. Conventional submarine design was based on electro chemical battery. The main issue in submarine is the elongation of its submerged endurance time as much as possible. Due to the gap between conventional submarine and the nuclear submarine it is essential to find alternative systems that must achieve the demand of power and stealth.

If the exhaust gas from a diesel engine is recycled with the carbon dioxide removed and oxygen added to form a synthetic atmosphere, the diesel engine can become a closed cycle system and function as an Air Independent Propulsion (AIP) source

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of underwater vehicles that have a high overall efficiency, safety, and high reliability [4,5].

Fig. 1 shows a closed cycle diesel engine in which the exhaust gas exits from the engine is recirculated as the EGR and fresh oxygen are injected into it in order to form a synthetic atmosphere. By this way, the diesel engine can function as an air independent power source of underwater vehicles [6–9].

Several researchers have studied a Closed Cycle Diesel Engine (CCDE) and different methods that enhance its performance. Karim and Klat [10] investigated experimentally the performance of compression ignition engine in nonconventional atmosphere to achieve reliable combustion of introducing small amount of hydrogen into compression ignition engines manifold.

Fowler [11,12] developed a closed-cycle diesel engine capable of providing the basis of a depth-independent, autonomous power-generation system. His system comprises a conventional diesel engine incorporating chemical scrubbing of the exhaust and oxygen replenishment, the reconstituted charge being recirculated to the engine's intake in a closed cycle. He found through the numerical simulation that the limitation of CO_2 concentration in the synthetic air was not exceeding 2–4% (by volume) to maintain the same specific ratio as that of atmospheric air.

Nour et al. [13,14] Studied the diesel engine performance experimentally on the bases of Synthetic Atmosphere for Recycle Operation. They found that there is performance deteriorating effects due to CO_2 % increase by volume and the beneficial effects due to O_2% increase by volume, in the engine inlet mixture.

Belal et al. [15] investigated DI diesel engine performance and emissions by using CFD code, and also they discuss the effect of hydrogen on CCDE power and fuel consumptions. They found that a promotion of the chemical reaction with hydrogen addition is mainly due to the increase of free radicals H, O, OH in the flame as a result of hydrogen addition. Hence, the heat release rate starting is advanced with the increase of hydrogen fraction while the combustion duration decreases.

Shaw and Oman [16] experimentally investigate a closed cycle diesel engine to understand the effect of using the inert gases (nitrogen, argon, helium, and carbon dioxide) on the ignition process of the engine. The result showed that taking

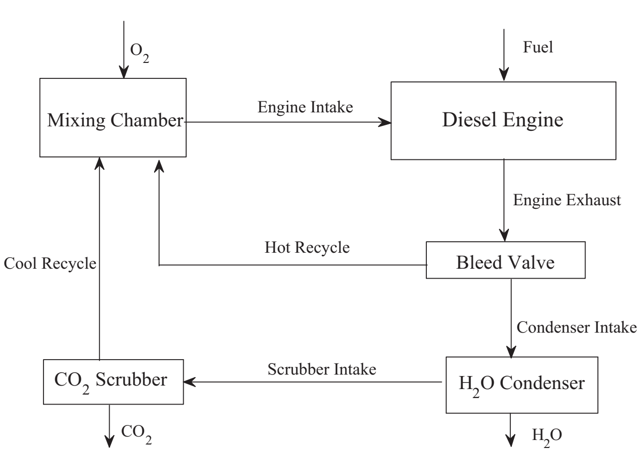

Figure 1 Operation principle of a closed cycle diesel system.

helium and Helium as inert gas would have better thermal efficiency because of higher specific heat ratio.

Horng et al. [17] carried out a numerical simulation for a closed cycle diesel engine (CCDE) with different intake gas contents of oxygen, argon, and nitrogen. They showed that the in-cylinder pressure increased with the increase of the percentage of argon.

From the above survey, it is found that there is a necessity for a detailed numerical investigation of a CCDE using recent and advanced simulating codes. Therefore, this paper aimed to enhance the performance of the CCDE by introducing helium into the intake mixture throughout the numerical modeling. The CFD model was performed with CFD simulation program ANSYS Fluent 14.0.

2. Numerical simulation

A fluid flow and heat transfer, species transport and fuel air mixture combustion are modeled then solved using ANSYS Fluent 14.0. The numerical model was validated by comparing its result with the results of an established experiment done by Nour et al. [13,14].

The CFD simulation was done for crank angle duration 230° i.e. simulation starts after intake valve closure at 59° after BDC and continues until exhaust valve opens at 71° before BDC. In order to simulate the real conditions of closed cycle diesel engine, the initial pressure and temperature are set to 1.5 bars and 346 K respectively.

Auto-ignition model is used for simulating the direct injection diesel engine. The fuel is injected into a gas which is usually air; however, it can contain a considerable amount of recirculated exhaust gas in order to reduce nitrogen oxide emissions (NOx). In the autoignition model, the ignition delay is assumed to be a function of the in-cylinder gas composition, pressure, temperature and the turbulence level. In addition, the ignition occurred when the ignition species within the engine combustion chamber reaches a value of one in the domain.

The average molecular weight, specific heat and specific enthalpy of species are calculated from JANAF [18] tables. Moreover, spray combustion consists of complex thermochemical processes involving fuel atomization, evaporation and combustion in the hot reactive turbulent gaseous environment. The description of the spray systems requires a detailed characterization of the exchange of the mass, momentum, and energy between the gases and the fuel droplets. The droplet parcels are injected through the fuel injector with specified initial conditions of droplet position, size, and velocity. Number of droplets in the parcels is determined according to the size distribution, injection velocity, initial spray angle, liquid fuel temperature, and injected fuel rate at the injector nozzle exit [19].

The GAMBIT grid generator has been used to generate the computational grid to simulate the real engine in-cylinder geometry. The quality of the mesh plays a major role in the accuracy and stability of the numerical computation. The dynamic grid is drawn when the piston is at the top dead center. Then the gird is updated during the simulation to the new size as a function of crank angle i.e. time. The computational grid is created and divided into two zones: first zone, is the clearance volume above the bowl and it is generated of hexahedron cells, while the mesh in the second zone is created from

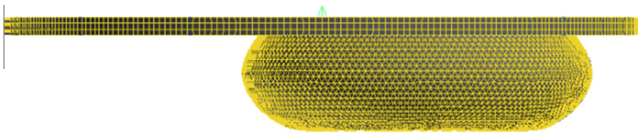

Figure 2 Computational Domain.

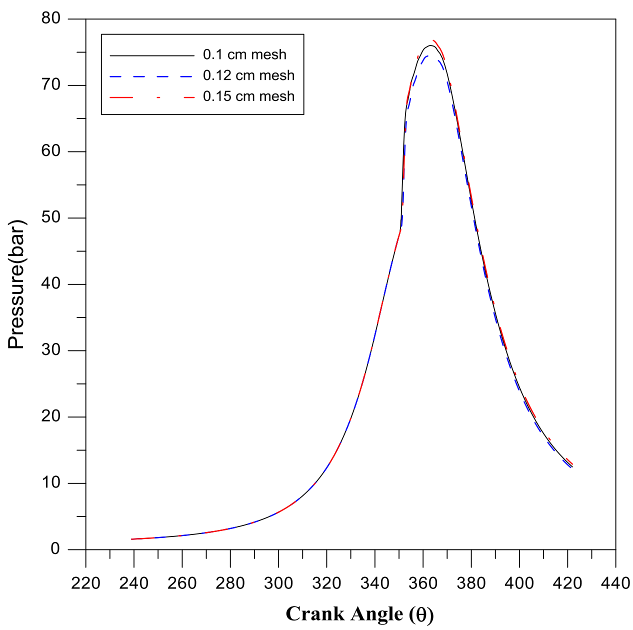

Figure 3 The comparison in-cylinder pressure of different mesh.

the tetrahedron type because of the geometry complexity of the piston bowl. The physical and computational domains are shown in Fig. 2.

Three different mesh sizes of 1.5, 1.2, and 1.0 mm have been compared for the purpose of the study of the grid independence. The results obtained of the different cases as shown in Fig. 3 are comparable to each other; therefore, a size of 1.2 mm cell and number of 174000 cells were taken in all simulation cases.

A numerical validation was conducted through a comparison of the numerical model results with the experimental results of Nour et al. [13,14]. Fig. 4 shows the comparison between the experimental and numerical pressure curves at engine speed of 1500 RPM running at full load condition with 10% carbon dioxide recycled. It is indicated that the simulated and measured in-cylinder pressure is in a good agreement; however, a slight deviation is exposed only during θ = 290–340 due to the fact that heat transfer is not taken into account in numerical simulation. In addition, the peak pressure of the simulation is higher than that of the measured value because the CFD simulation neglects the friction losses.

3. Results and discussion

The CFD model was used to simulate the diesel engine cycle with different intake gas contents adopting different proportions of the oxygen, helium, and nitrogen under different engine loads. The calculations have been performed firstly with

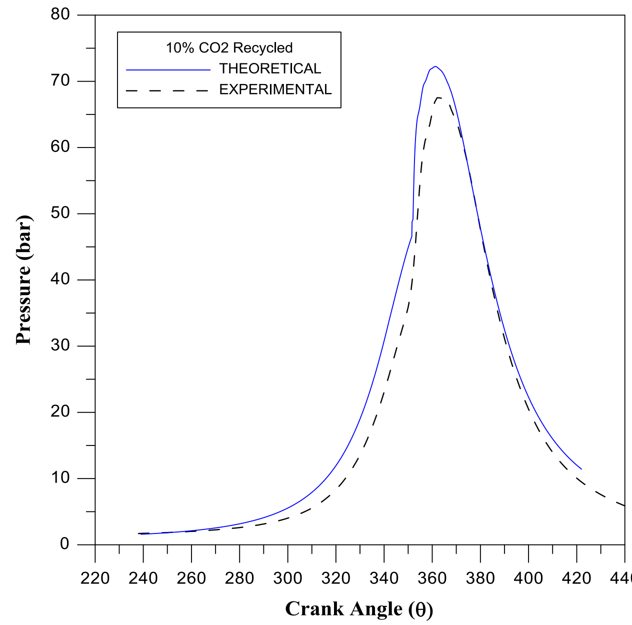

Figure 4 The comparison in-cylinder pressure between theoretical and experimental of full load with 10% CO_2 recycled.

Table 1 The detailed definitions of the intake contents.

Intake contents by weight/full load	O_2	CO_2	He	N_2
Normal air	0.2329	0.00383	0	0.7671
5% CO_2 &0%He	0.2266	0.0742	0	0.6992
5% CO_2 &0.5 %He	0.2276	0.0745	6.7772e−004	0.6972
5% CO_2 &1%He	0.2285	0.0748	0.0014	0.6953
10% CO_2 & 0% He	0.2207	0.1445	0	0.6348
10% CO_2 & 8% He	0.2355	0.1543	0.0112	0.5990
10% CO_2 & 10% He	0.2396	0.1569	0.0143	0.5893
15% CO_2 &0% He	0.2150	0.2112	0	0.5737
15% CO_2 &0.5% He	0.2159	0.2121	6.4289e−004	0.5714
15% CO_2 &1% He	0.2167	0.2129	0.0013	0.5691
20% CO_2 &0% He	0.2097	0.2746	0	0.5157
20% CO_2 &0.5% He	0.2105	0.2757	6.2679e−004	0.5132
20% CO_2 & 5.5% He	0.2187	0.2864	0.0072	0.4877
25% CO_2 &0% He	0.2046	0.3349	0	0.4605
25% CO_2 &3% He	0.2091	0.3424	0.0037	0.4447
25% CO_2 &6% He	0.2139	0.3503	0.0076	0.4281

the intake gas contents without helium injection which was composed from N_2 = 0.78%, O_2 = 0.21 %, CO_2 = 0.0% and this mixture was taken as a reference mixture.

The detailed compositions of the intake contents are listed in Table 1. Helium concentration percentages on mass basis which are involved in this study are 0. 5 %, 1%, 3%, 6%, 8% and 10%.

Fig. 5 shows the variation of in-cylinder pressure with the crank angle under different load conditions. This figure indicates that in-cylinder pressure is directly proportional to engine load at the same percentage.

Fig. 6 represents the comparison of the simulated full load engine with different concentrations of recycled He added in the intake content. Maximum in-cylinder pressure is attained

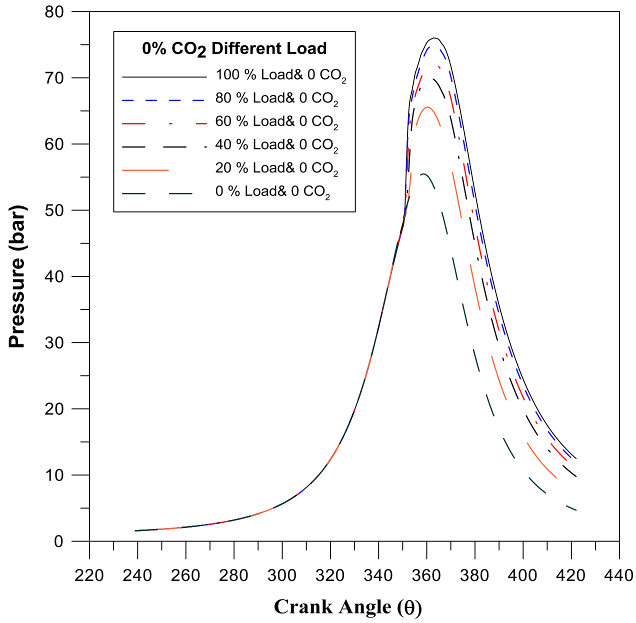

Figure 5 Theoretical in-cylinder pressure of different load with 0.0% CO_2 recycled.

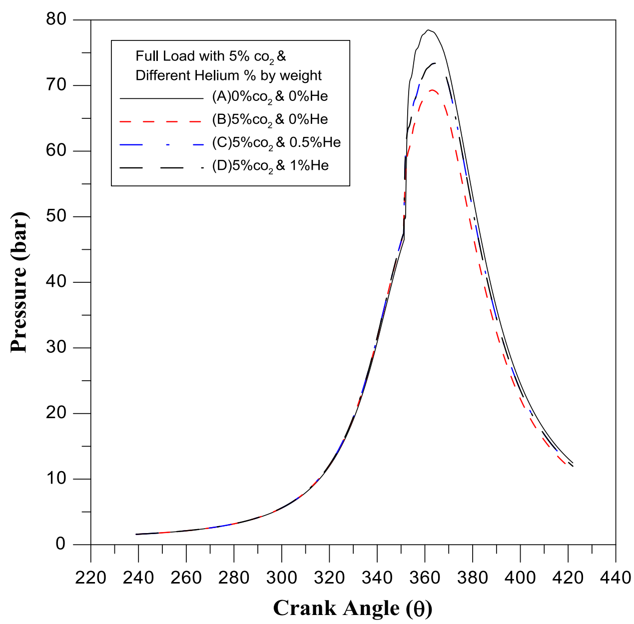

Figure 6 Theoretical in-cylinder pressure of full load with 5% CO_2 and different % of Helium.

when there is no CO_2 in the gas, and deterioration of in-cylinder pressure due to adding of CO_2 recycled is clear in case (B). A recovery in in-cylinder pressure was achieved by using 0.5% helium and almost the same recovery % obtained by using 1% helium as the maximum recovery can be achieved. The deterioration of engine power is due to severe effect of using CO_2 as a recycled gas and this is due to the fact that CO_2 is a tri-atomic gas, with relatively low ratio of specific heat and hence a decrease in total intake mixture specific heat and therefore decreasing the cycle pressure and temperature. The

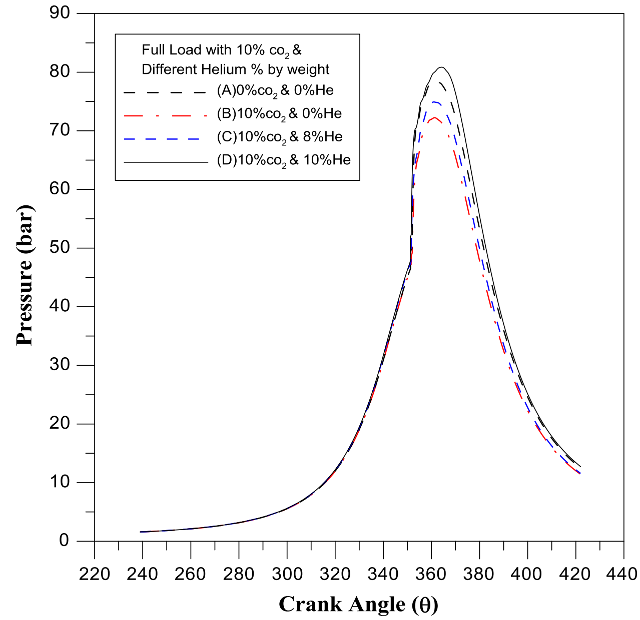

Figure 7 Theoretical in-cylinder pressure of full load with 10% CO_2 and different % of Helium.

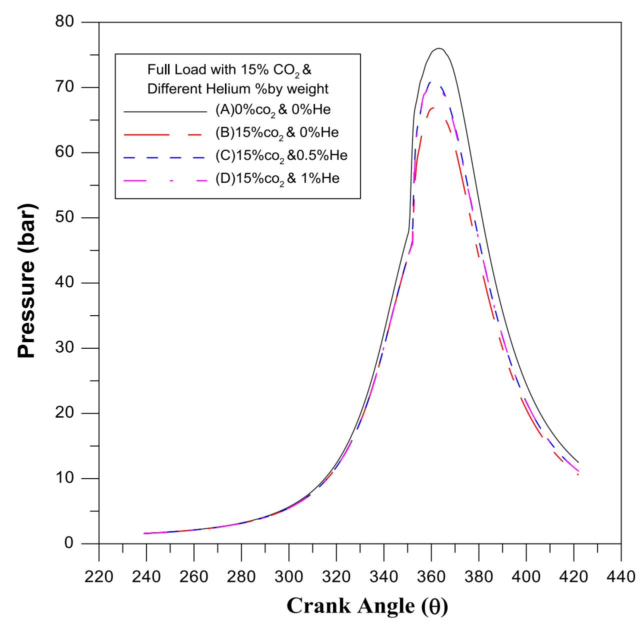

Figure 8 Theoretical in-cylinder pressure of full load with 15% CO_2 and different % of Helium.

gain of power achieved when replacing CO_2 with a mono-atomic helium gas with high specific heat improves the total intake mixture thermal properties.

Fig. 7 shows that 10% CO_2 leads to maximum reduction in in-cylinder pressure and this reduction can be overcome by injecting 8% helium in the intake manifold. Fig. 7 also shows that the maximum recovery of the engine power can be obtained by using 10% helium as a replacement of CO_2.

Figs. 8–10 show the same trend as the previous figures. A deterioration of the in-cylinder pressure due to usage of

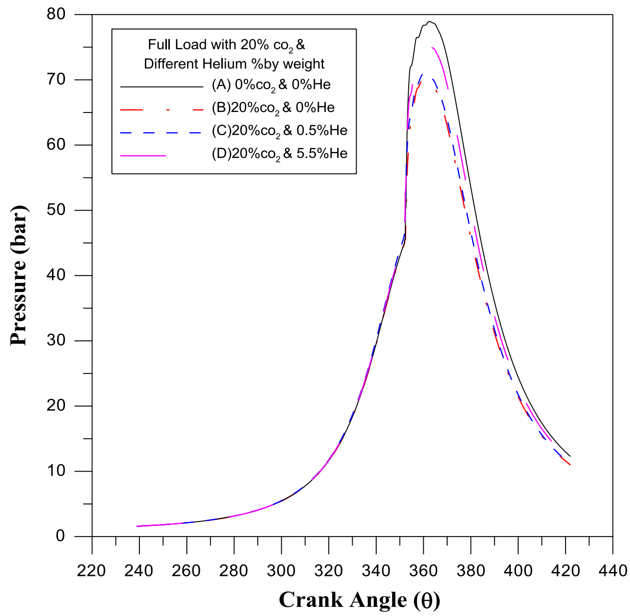

Figure 9 Theoretical in-cylinder of full load with 20% CO_2 and different % of Helium.

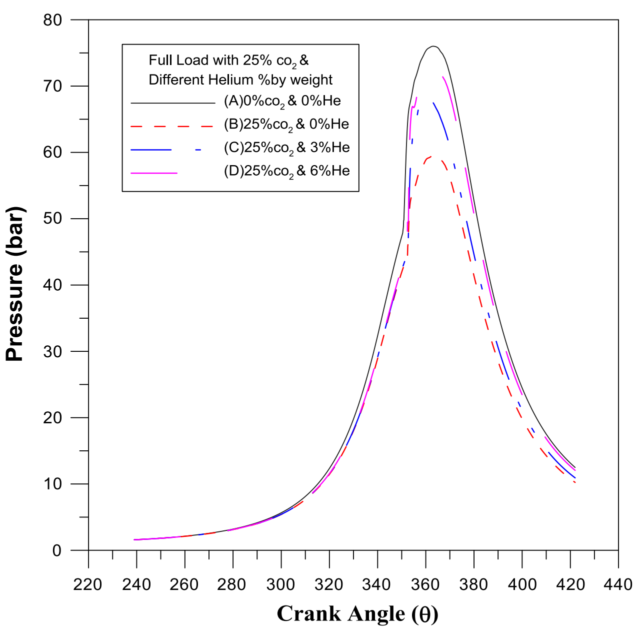

Figure 10 Theoretical in-cylinder pressure of full load with 25% CO_2 and different % of Helium.

15%, 20% and 25% of CO_2 is shown in these figures. The power recovery can be achieved by recycling 1%, 5.5%, and 6% of helium into the intake gases.

Since the molar mass of He is less than N_2, and the rate of diffusion is inversely proportional to the square root of their densities, the diffusion rate of He is higher than N2. Hence, the rate of combustion is extraordinarily increased. In addition, the specific heat ratio of the He is higher than that for N_2 and this leads to an increase in the engine thermal efficiency.

4. Conclusions

Three dimensional numerical combustion model was validated and its results was used to show the effect of introducing Helium into the intake manifold of closed cycle diesel engine under different load conditions. The main conclusions derived from this study can be listed as follows:

- o As the concentration of helium increases, the mean cycle pressure increases and hence adding helium has better effect on the heat transfer and combustion process.
- o There is a certain limit of using CO_2 as a recycled gas and as a replacement gas instead of N_2, the limitation was found to be 25% by weight.
- o A percentage of 0.5–10% of helium on mass basis is sufficient in the recovery needed to overcome the drop in-cylinder pressure and hence power due to the existence of CO_2 in the recycled gas up to 25%. When the CO_2 % reaches 25%, it is required to use at least 10% of He as replacement gas to achieve the required recovery.
- o By introducing helium into the CCDE, the amount of scraper solution used in removing CO_2 from exhaust gases is reduced and hence the size of CCDE system is reduced, which has a great impact on the submarine design technology.

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