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Study of Diesel Combustion Combined with Hydrogen using an Industrial Burner

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Abstract

Facing the challenges of fossil fuel depletion and greenhouse gas emissions, there is an urgent need to study and find new energy sources that are both efficient and non-polluting. This research aims to investigate the effects of using hydrogen as a co-combustion fuel with diesel oil on the temperature and hot gas emissions using a Computational Fluid Dynamics (CFD) simulation. The model was designed to match the characteristics and dimensions of a real experimental combustion setup, consisting of a combustion chamber, an inlet for diesel fuel, an air inlet for both combustion air and hydrogen, and an outlet stack for the hot gases. To validate the model prior to its application, a pure diesel combustion case was experimentally tested and compared with the simulation. The results confirmed that the model is sufficiently accurate for use, as the experimental and simulation results showed similar trends and behaviors. The flow rates of diesel and hydrogen were determined based on the calorific ratio that yielded the same total heat energy input to a combustion chamber. The studied ratios were 77:23 of diesel to hygrogen based on heating value. For each case, the combustion air flow rate was adjusted to achieve equivalence ratios (ϕ) of 0.65, 0.8, 0.95, and 1.1. The findings show that using hydrogen as a co-fuel results in a higher combustion temperature and a reduction in carbon dioxide (CO_2) emissions compared to pure diesel combustion. Specifically, as the hydrogen ratio increases, the resulting temperature increases and the amount of CO_2 decreases. Notably, combustion at an equivalence ratio (ϕ) of 1.1 resulted in the highest temperature and CO_2 emissions among the tested equivalence ratios.

1. Introduction

Currently, a significant amount of greenhouse gases is being released into the Earth's atmosphere, causing the Earth's average temperature to rise. Carbon dioxide is one of the most heavily released greenhouse gases into the atmosphere due to its close connection with daily human life. One of the factors contributing to greenhouse gas emissions is the use of fossil fuels, which are hydrocarbon compounds. When combustion occurs, carbon dioxide gas is produced as a product. Consequently, the world has turned its attention to using other renewable energies to replace the significantly decreasing amount of fossil fuels and to reduce greenhouse gas emissions [1]. As a result, many research studies have emerged concerning renewable energy sources and their application methods. Several studies have investigated the use of alternative fuels to replace diesel or fuel oil used in industrial factories [2]-[7]. Furthermore, there is research studying the effects of mixing alternative fuels with diesel or fuel oil [8-13].

Ahmed et al. [14] studied the combustion characteristics of using waste cooking oil (WCO) as a fuel compared to light diesel oil (LDO) using an experimental combustion chamber setup. This research found that WCO exhibited reduced NO_x and CO emissions, greater heat transfer to the furnace walls, and a flame with less soot compared to LDO. Additionally, the study showed that an increase in the equivalence ratio led to an increase in exhaust gas temperature and a larger flame size. Nozomu et al. [15] conducted combustion experiments using fuel oil and a mixture of fuel oil and Jatropha oil in a 50:50 ratio. They collected inlet and outlet water temperatures to calculate heat energy absorption and measured the amount of NO_x and SO_2 in the soot. Comparing the results, they found that the addition of Jatropha oil led to a reduction in soot formation, and consequently, lower flame radiation intensity and heat absorption. Muhammad Ahmar et al. [16] investigated the combustion efficiency obtained from using sludge palm oil as a fuel. They found that the oil sludge possessed properties suitable for fuel use, but it required high-temperature preheating. It had a lower temperature than diesel but emitted lower quantities of CO, CO_2, and NO_x in the exhaust gas compared to diesel by 34%, 6%, and 90%, respectively. The above research findings indicate that the efficiency of other alternative fuels, including fuel blends, is still less than that of diesel and fuel oil. However, they show lower soot emissions. It is evident that fuel blending leads to a reduction in soot and exhaust gas emissions, making it interesting to explore: If a clean fuel like hydrogen were mixed or co-fired with fossil fuels, would it help in reducing greenhouse gas emissions.

Another alternative that has received the most attention recently is Hydrogen energy. This is due to its classification as a clean alternative energy source, possessing a high heating value and combustion efficiency comparable to oil, and producing no pollution during use. Therefore, studies have been conducted on using hydrogen as a co-fuel in the combustion of primary fuels. For example, Kuntang et al. [17] investigated the combustion characteristics and performance of a diesel engine using palm biodiesel and hydrogen gas as fuel. They utilized a single-cylinder, direct-injection diesel engine (DDF). Hydrogen gas was injected into the intake manifold along with the combustion air to determine the effect of the hydrogen flow rate on the cylinder pressure, heat release rate, ignition delay, knocking, power, brake thermal efficiency, and specific fuel consumption of the engine, compared to the case of using biodiesel alone. However, the use of hydrogen for combustion experiments comes with limitations and dangers, including its easy flammability in the event of a leak or the risk of flame flashback.

Currently, Computational Fluid Dynamics (CFD) simulation is widely used in various applications, including the design of diverse equipment and tools, the analysis of chemical reactions, and the prediction of physical behaviors. CFD is an effective tool that not only helps address issues of cost, time, and safety but also assists in analyzing data that is difficult or impossible to measure during real-world experiments [18]-[23]. Therefore, this research aims to study the co-firing of hydrogen with a liquid fossil fuel using an industrial burner via CFD simulation. The results obtained from this study can serve as supporting data for making decisions about the selection of alternative fuels and can be used as a guideline for reducing greenhouse gas emissions in the industrial sector.

2. Methodology

2.1 Experiment

2.1.1 Experimental Setup

The experimental setup used for the combustion of pure diesel fuel is shown in Fig. 1. It is installed within the Department of Mechanical Engineering, Prince of Songkla University, Hat Yai Campus. The main components include: an industrial oil burner, a fuel and air delivery system, and a combustion chamber with a diameter of 45 cm and a length of 185 cm. The chamber is internally divided into nine sub-sections, assembled with a water-cooling system and an exhaust pipe. The side surface of the combustion chamber, the water inlet/outlet pipes and the exhaust pipe have ports for inserting thermocouple probes. The ends of each probe are connected to thermocouple wires, with the other end connected to a data logger (Hioki LR8400-20 from Japan) for measuring the flame temperature inside the combustion chamber, the inlet/outlet water temperatures, and the hot gas temperature. An industrial burner (NU-WAY MOL200 S1L from Sweden), which operates only in a single stage and a single fuel nozzle, was used. The air inlet of the burner was connected to an orifice flow meter and an external ring blower. This ring blower was used for varying air flow rates to control equivalence ratios. This experimental

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setup will be used to test the combustion of pure diesel fuel to obtain data for comparison with the simulation results in order to validate the model.

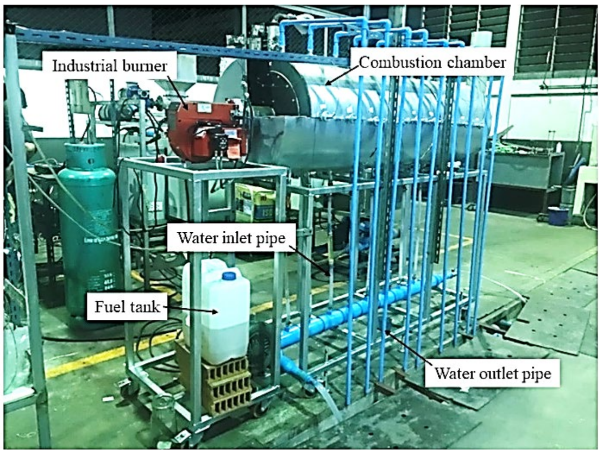

Fig. 1 *A photo of the experimental setup of the diesel combustion system*

2.1.2 Measurement

To begin the experiment, diesel oil was sucked by a high-pressure pump assembled in the industrial burner for injecting fuel to be atomized through the burner's nozzle (nominal size of 1.35 gph). The air flow rate will be varied according to the fuel-to-air ratio used, corresponding to equivalence ratios (Φ) of 0.65, 0.8, 0.95, and 1.1, as shown in Table 1. The data logger records the flame temperature obtained during each combustion period.

2.2 Computational Fluid Dynamics (CFD)

2.2.1 CFD Model

A Computational Fluid Dynamics (CFD) based on finite volume was applied in this work. The ANSYS Fluent 2019 R3 software was used to design the combustion chamber model based on the experimental setup as previously shown in Fig. 1. The created model has the same dimensions as the actual combustion chamber. Its main components include a fuel inlet for diesel oil, an air inlet for air and hydrogen, the combustion chamber walls, and an outlet for exhaust gas, as illustrated in Fig. 2.

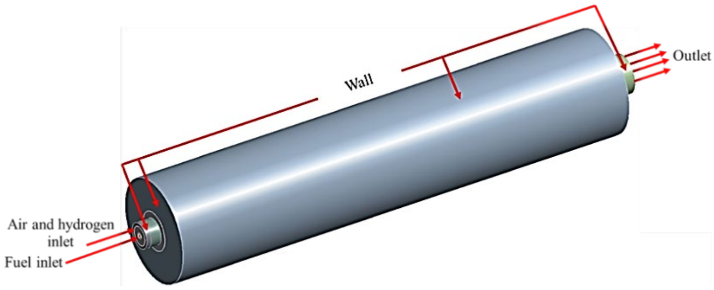

Fig. 2 *Combustion chamber model*

2.2.2 Mesh Generation and Mesh Independent Study

Mesh generation is another crucial aspect of simulation. The higher the quality of the generated mesh, the easier the simulation will converge, and the more accurate the results will be. Therefore, the MultiZone meshing method was chosen because it is easy to use and efficiently generates hexahedral (or cubic) meshes. This approach provides high-quality meshes with an appropriate number of cells. The result of the mesh generation for the model is shown in Fig. 3, where it can be seen that the resulting mesh consists of quadrilateral shapes both outside and inside the model. Fig. 4 illustrates the simulation results obtained from different mesh counts. Upon consideration, it was found that the mesh counts of 1,040,844 and 1,156,282 cells yielded almost similar simulation results. Therefore, to ensure accuracy and minimize the computational time required, a mesh with 1,040,844 cells was selected for the combustion study in this research.

Fig. 3 *External and internal mesh of the CFD model*

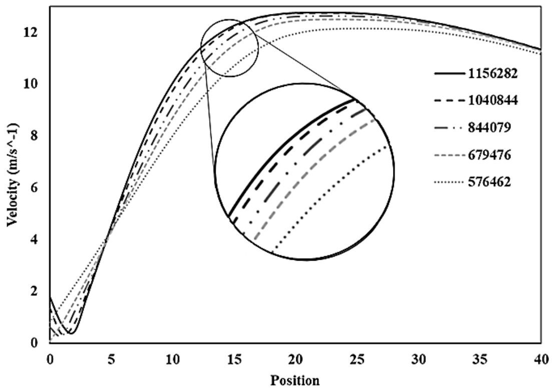

Fig. 4 *Mesh independent study*

2.2.2 Boundary Conditions and Calculation

The key variables for controlling combustion at various equivalence ratios (Φ) are the flow rates of fuel and air. The thermal input of diesel combustion and diesel-hydrogen co-combustion was controlled under the same heating value. The flow rates of fuel and air used in the simulation for both pure diesel combustion and diesel-hydrogen co-combustion (at a heat input ratio of 77:23 between diesel and hydrogen) are shown in Table 1. The combustion chamber exit was set as a pressure outlet at atmospheric pressure and room temperature. The combustion chamber surfaces were set as an isentropic non-slip wall.

Table 1 *Fuel and air flow rates for combustion*

Fuel	ER	Fuel inlet (g/s)		Air inlet (g/s)	
		Phase diesel	Phase hydrogen	Phase diesel	Phase hydrogen
Diesel 100%	0.65	1.443	0	32.175	0
	0.80			26.142	
	0.95			22.015	
	1.10			19.013	
Diesel 77% & hydrogen 23%	0.65	1.110	0.121	24.759	6.362
	0.80			20.117	5.169
	0.95			16.941	4.353
	1.10			14.630	3.760

Since the simulation involves the flow of different fuels, the Volume of Fluid (VOF) model was chosen for the multiphase model. Additionally, because the fluid flow in this combustion simulation is far from the walls, the Standard k-epsilon (k−ε) turbulence model, along with the Standard Wall Function equations, was employed to describe the fluid viscosity. To describe the chemical reaction of combustion, the Eddy Dissipation Model (EDM) was selected, as it is a widely used model for combustion simulations. The numerical calculation method selected for the simulation is the second-order upwind scheme, and the calculation scheme was SIMPLE. The simulation is considered complete when the convergence criterion is met at a residual value of 1×10^{-3}.

3. Results and Discussion

3.1 Validation of CFD Results

Fig. 5 presents a comparison of the experimental and simulation results. The hot gas temperature profiles obtained from both the experiment and the simulation exhibit a similar trend. Specifically, a peak temperature is observed at the burner exit, followed by a sharp/steep decrease within the first 40 cm downstream of the burner exit. Subsequently, the temperature gradually declines, becoming nearly constant with increasing distance from the burner exit. Upon closer comparison, the simulation results yield a higher temperature than the experimental data. This discrepancy is primarily attributed to heat loss of the flame and hot gas to the combustion chamber walls in the experimental setup, which subsequently leads to a reduction in the measured flame and hot gas temperatures as compared to simulation work.

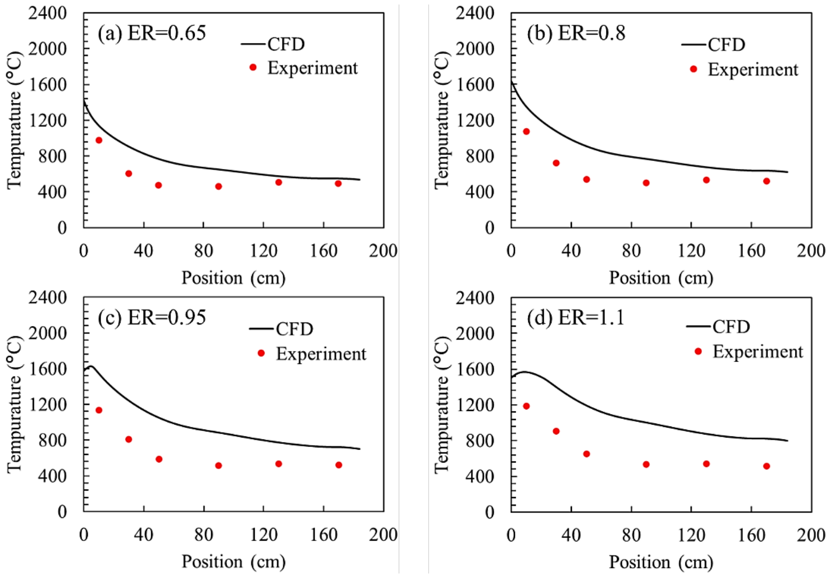

Fig. 5 *Flame and hot gas temperature along the centerline of combustion chamber (experimental and simulation results)*

3.2 Flame Physical Characteristics

Flame physical characteristics of diesel and diesel-hydrogen combustion from experimental and simulation results are shown in Fig. 6. It can be summarized that the flame from the experiment (Diesel100%) at an equivalence ratio (Φ) of 0.65 (Fig. 6(a)) had the shortest length, while the longest length occurred at an equivalence ratio of 1.1 (Fig. 6(j)). In the range of equivalence ratios from 0.8 to 0.95 (Figs. 6(d) and (g)), the flame sizes were similar, but the flame at an equivalence ratio of 0.95 showed only a slightly higher intensity. This trend is consistent with the CFD simulation, although the differences in flame size were more clearly distinguishable in the simulation results. When considering the case of addition of hydrogen from simulation work (Figs. 6(c), (f), (i) and (l)), at the same equivalence ratio, the flame from the diesel-hydrogen co-combustion is longer than the flame from the pure diesel combustion. This phenomenon is attributed to the higher calorific value of the added hydrogen compared to diesel, which consequently results in a longer high-temperature region than in the case without hydrogen addition.

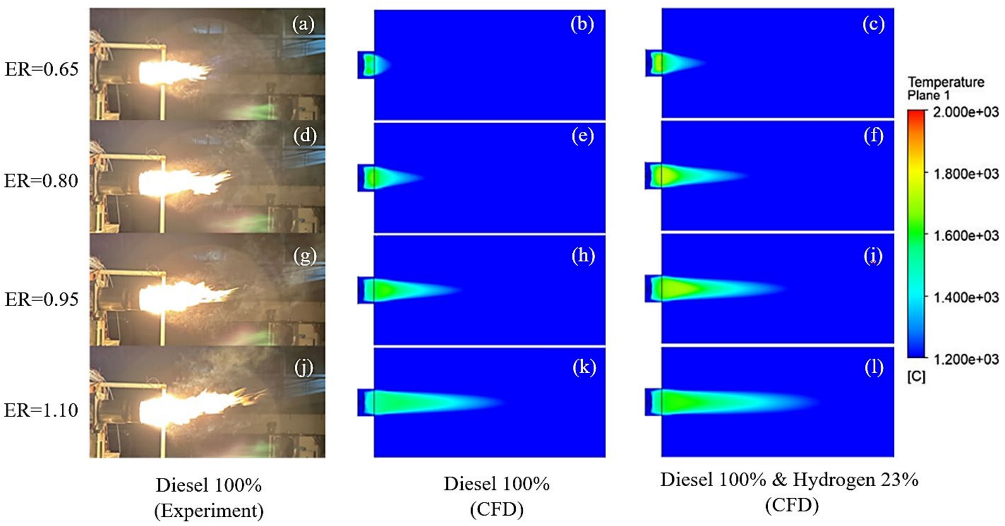

Fig. 6 *Flame characteristics of diesel and diesel-hydrogen combustion (experiment and simulation results)*

3.3 Flame and Hot-Gas Temperatures

Flame and hot-gas temperatures along the centerline of the combustion chamber from simulation results are shown in Fig. 7. The flame and hot-gas temperatures for both neat diesel and diesel-hydrogen co-combustion are observed to decrease with an increasing equivalence ratio (Φ). A lower equivalence ratio (Φ<1) signifies a higher proportion of oxidizer (being air in this work). The resulting temperature decrease is attributed to this excess air, which contains approximately 79% nitrogen. Nitrogen is considered an inert diluent in the combustion process; since it does not participate in the combustion reaction, it acts as a heat sink, effectively reducing the temperature within the combustion chamber.

Comparison of flame and hot-gas temperature along the centerline of the combustion chamber between the diesel combustion and diesel-hydrogen co-combustion from simulation work is shown in Fig. 8. As illustrated in the figure, the addition of hydrogen results in a higher flame temperature compared to the neat diesel case. In this study, the total heating value input to the combustion chamber was controlled; specifically, the hydrogen-enriched cases at various equivalence ratios (ERs) had the same total heating value input as the case using diesel fuel alone. Therefore, the observed increase in flame temperature with hydrogen addition can be explained by chemical kinetics. Hydrogen possesses fewer chemical bonds than hydrocarbon fuels, which facilitates a faster chemical reaction rate compared to the slower combustion of the hydrocarbon component. Consequently, even when the two fuel types have an identical heating value input, the hydrogen-enriched combustion achieves a higher temperature than the case without hydrogen addition.

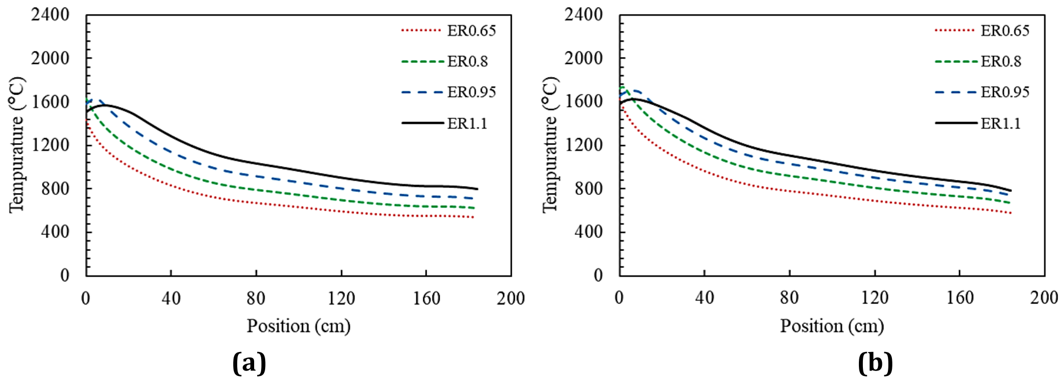

Fig. 7 *Flame and hot-gas temperature along the centerline of the combustion chamber (simulation results) (a) Diesel 100%; (b) Diesel 77% and hydrogen 23%*

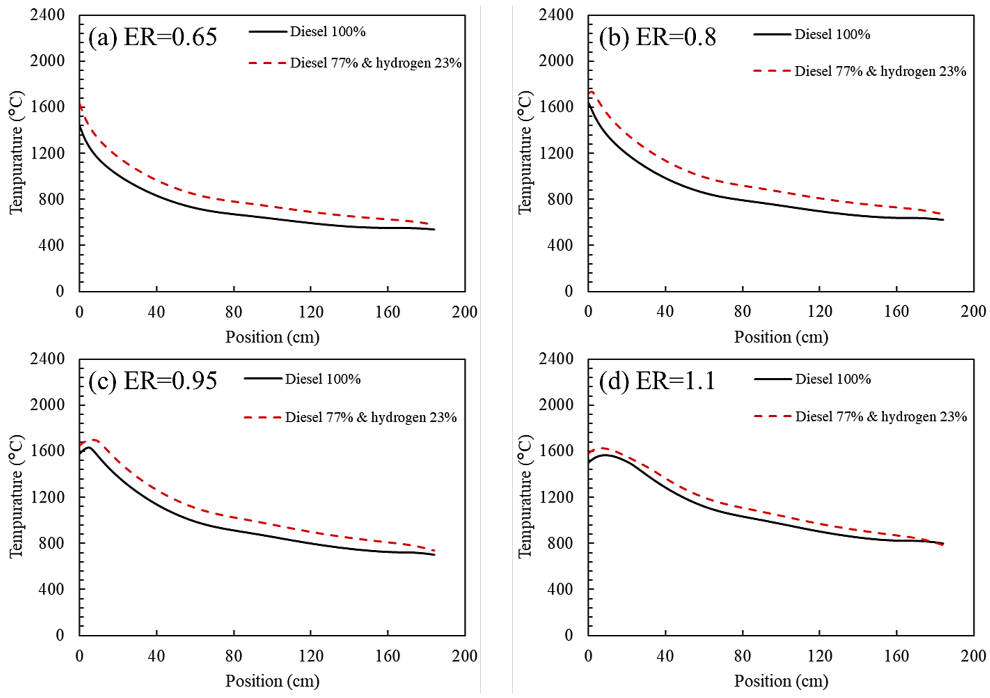

Fig. 8 *Comparison of flame and hot-gas temperature along the centerline of the combustion chamber between the diesel combustion and diesel-hydrogen co-combustion (simulation results)*

3.4 Combustion Products

Combustion products of flue gas of diesel and diesel-hydrogen combustions from simulation work are shown in Fig. 9. In general, a low concentration of oxygen and a high concentration of carbon dioxide in the flue gas are indicative of complete combustion. In this study, an increase in the equivalence ratio (Φ) leads to a decrease in oxygen concentration and a corresponding increase in carbon dioxide concentration. Fig. 9(a), the amount of oxygen obtained from the diesel-hydrogen co-combustion is less than that from pure diesel combustion, which is most clearly observed at an equivalence ratio of 0.65. When the equivalence ratio is 0.8 and 0.95, the resulting oxygen quantities become much closer but still show less oxygen from the diesel-hydrogen co-combustion. At an equivalence ratio of 1.1, both cases yield the most similar oxygen quantities. Fig. 9(b), the amount of Carbon Dioxide (CO_2) obtained from both combustion cases follows the same trend: as the equivalence ratio increases, the amount of emitted CO2 increases accordingly. Notably, the CO2 from the diesel-hydrogen co-combustion is lower than that from pure diesel combustion. This represents another significant advantage of utilizing hydrogen as an alternative to hydrocarbon fuels in combustion systems: the potential for reducing CO2 emissions, which contributes to the greenhouse effect.

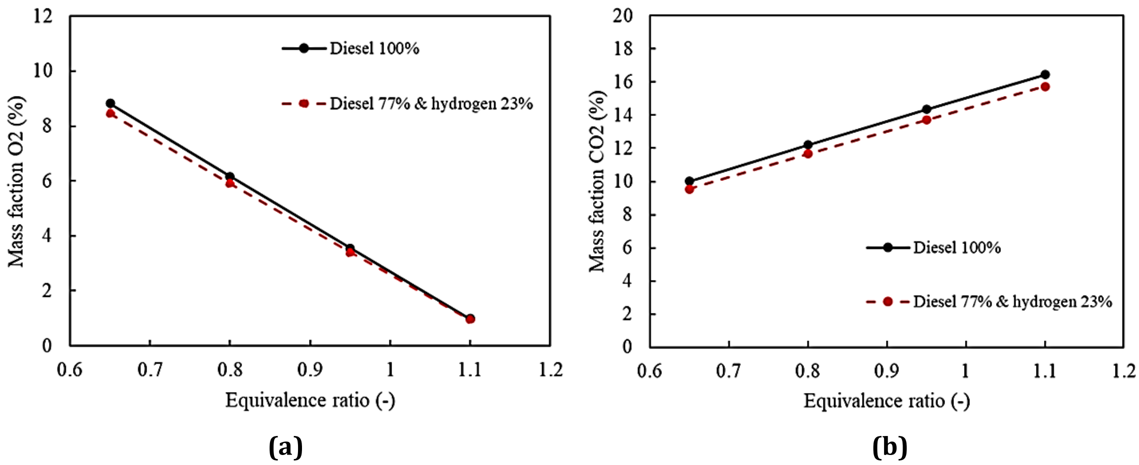

Fig. 9 *Combustion products of flue gas (simulation results) (a) Oxygen; (b) Carbon dioxide*

4. Conclusions

This research investigated the effect of using hydrogen as a co-fuel in diesel combustion on the combustion characteristics using a Computational Fluid Dynamics (CFD) simulation. The studied quantities of diesel and hydrogen were controlled by the same total heating value input. The ratio of diesel and hydrogen was 77:23, which is equivalent to the thermal energy obtained from pure diesel combustion. The findings are summarized as follows:

1. Using hydrogen as a co-fuel in combustion resulted in higher flame and hot gas temperatures compared to using pure diesel, when compared at the same equivalence ratio.
2. The temperature increased with the increasing equivalence ratio, reaching the highest temperature at an equivalence ratio of 1.1.
3. Using hydrogen as a co-fuel in combustion emitted a lower amount of carbon dioxide compared to using pure diesel, when compared at the same equivalence ratio.
4. The amount of carbon dioxide obtained increased as the equivalence ratio increased, with the highest amount occurring at an equivalence ratio of 1.1.

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Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of the paper.

Author Contribution

The authors are responsible for the study conception, research design, data collection, data analysis, result interpretation and manuscript drafting.

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