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AN EXPERIMENTAL INVESTIGATION ON THE COMBUSTION AND EMISSIONS OF HEAVY DIESEL-WATER EMULSION IN INDUSTRIAL BURNER

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Abstract

Boilers and marine engines use heavy fuel oil to produce mechanical and electric power, which is characterized by a high molecular weight, high viscosity, high asphaltene content, and complex compositional diversity. It causes an uneven spray pattern and imprecise injection viscosity. This study aims to mitigate the problem of heavy fuel oil to enhance the combustion of industrial burners. The mitigation proposal is to produce mixed heavy diesel with light types of diesels at a ratio of 50% each and call to reduce the viscosity and improve the fuel properties. The mixture is named heavy/light diesel fuel (HLD). The HLD fuel and distilled water were combined with Span-80 (1% of the final emulsion volume) to produce emulsions (E) at water-to-fuel 10%, 15%, and 20% vol. The prepared fuel was combusted in a combustion chamber to characterize the combustion performance and the exhaust composition. The experimental results showed that the percentage of NOx formation decreased as the percentage of water in the emulsion increased. When comparing E10% with pure HLD at air/fuel ratios of 20, 25, 30, 35, and 40% vol., the percentage of NOx formation decreased by 24.5%, 25%, 38%, 33%, and 67%, respectively. When comparing the results of E15% with pure HLD, the percentage of NOx formation decreased by 40%, 45%, 61%, 73%, and 67%, respectively, and when comparing the results of E20% with pure HLD, the percentage of NOx formation decreased by 58%, 70%, 76%, 73%, and 67%, respectively. Also, the results showed that the rate of fuel consumption decreased by 2.4%, 5.9%, and 14% from the combustion of E10%, E15%, and E20%, respectively, when compared with pure HLD.

Keywords: Diesel emulsion, Emissions, Fuel technology, Heavy fuel oil, Thermal efficiency.

1. Introduction

Lighter gases and distillation fuels are extracted from crude oil during the refining process. They have higher hydrogen-to-carbon ratios, are more costly, and generate more energy. The leftover residue oil from refining with high carbon content and low hydrogen content is known as heavy fuel oil (HFO) [1]. There is an increasing interest in the use of heavy fuel oil (HFO) in furnaces, boilers, marines, and recently in gas turbines [2]. However, HFO is primarily used as fuel to generate electricity in marine engines and boilers [3]. Many industries, such as cement, gypsum, and road asphalt productions, rely on HFO because of the large amounts of fuel they burn. However, the emissions they produce, which include nitrogen oxides and carbon monoxide, are relatively large. These emissions are a burden on the named industry, and they struggle to find more effective methods to reduce these emissions [4].

Economically speaking, HFO is a sought-after commodity because of its accessibility, affordability, and high energy density. Through the uneven mixing of thousands of individual molecules and functional groups into the fuel, asphaltene creates a non-homogenous fuel mixture. Among the characteristics that set HFO apart are its high viscosity, high molecular weight, high asphaltene content, and complex compositional diversity. It also generates harmful gases like NOx. The result is atomizer fouling, which leads to an incorrect injection viscosity and an uneven spray pattern. Furthermore, incomplete combustion caused by large fuel particles will result in incomplete vaporization and high exhaust gas particulates, which are primarily unburned hydrocarbons with varying amounts of ash from metals like sodium, vanadium, and other metals. It also releases toxic gases like Sox and NOx [5, 6].

The simplest, least expensive, and most efficient way to enhance combustion in fuel oil is to add water, which leads to reducing the flame temperature and thus reducing the formation of nitrogen oxides. Applying water to the fuel in the form of emulsified fuel is the most widely used technique for doing this. The droplet size must be right, even enough to evaporate quickly but large enough to go into the combustion chamber. The droplet size must also be controlled to achieve appropriate combustion conditions [7, 8].

The emulsion is a combination of two different fluids that are not physically mixed; instead, they are suspended in one another. There are two-phase and three-phase emulsions available. The two-phase emulsion is influenced by the kind and capacity of the blending, surfactant, and isolated as well as continuous phases [9]. The addition of more surfactants preserves the emulsion's stability. Simply put, surfactants ought to burn entirely without producing any more gases or changing the characteristics of the fuel [10, 11].

Moreover, they must not affect the fuel's physicochemical characteristics. Typically, 1%-2% of the volume ratio of surfactant is needed to create the emulsion. An emulsion of water in regular diesel that has been stabilized with surfactants is known as the W/O emulsion fuel. Standard surfactants, such as sorbitan monooleate (Span 80) and ethoxylated sorbitan monooleate (Tween 80), have been used [12, 13].

When using the emulsified liquid as a fuel, the first step of atomization is usually achieved using a spray nozzle. The second stage of atomization is completed when the droplets enter the high-temperature combustion chamber and cause a microexplosion. Consequently, secondary atomization occurs, causing the droplets to fragment into tiny droplets that are easily vaporized and ignited. This process improves the formation of the combustible mixture as well as its combustion efficiency. Another advantage of using emulsified fuel is that its moisture absorbs heat to lower the flame temperature and thereby prevent thermal NOx formation [14-17].

Due to the size of the fuel drops during combustion, the available time for combustion is insufficient to completely burn them; in contrast, the emulsion drops are small because of the partial explosion that permits full combustion. [18, 19]. The temperature rises, and the time it takes for a simple explosion to occur increases with the high emulsion content. The strength of the precise explosion of W/O and O/W depends on the distributed liquid diameter and the environmental factors [20].

The different steam points of these liquids have an impact on how quickly water and fuel evaporate. Water molecules disintegrate steam growth and lower the flame temperature, which prevents the production of soot, PM, NOx, CO, and other pollutants because they are concentrated early in fuel molecules [21]. The micro-explosion causes the atomization of the fuel molecules and thus facilitates the communication of the fuel molecules with the air. This leads to complete combustion, which in turn maintains the efficiency of combustion [22].

Iraq is an oil-producing country and has a large stock of cheap HFO compared to LFO prices. This study aims to provide fuel of appropriate quality at reasonable prices, considering reducing toxic emissions and maintaining good burner performance. To accomplish this, 50% heavy diesel and 50% light diesel are mixed to create HLD fuel, which is then heated to reduce viscosity and density.

Then, water is added to the HLD fuel in three different ratios of 10, 15, and 20%. Furthermore, the process's impact on the burner's operation and the pollutants it emits are assessed. This research aims to propose a novel fuel blend that has the potential to supplant heavy diesel fuel while maintaining economic viability through cost reduction.

2. Experimental Methods

The tools and methods required to complete this experiment are described in this section. It explains how the fuel was used, how the testing samples were prepared for this experimental work, how the operational parameters were measured, and how exhaust gas emissions were measured. In experimental work, for various mixing air-to-fuel (A/F) ratios of 20, 25, 30, 35, and 40. Figure 1 provides clarification on this work device. A combination of light and heavy diesel fuel was used in the experiments to evaluate the burning's efficiency and emissions.

2.1. The test rig

The combustion chamber is made of 1.5 mm in thickness 316 stainless steel. It has a cylindrical shape with a 440 mm internal diameter and 1000 mm length. The burner is surrounded by an external shell, making a gap of 30 mm annulus, allowing cooling water flow to extract the heat generated inside the combustion chamber. This model has a thermal output of 25 to 90 kW under fuel consumption of 2.5 to 8 kg per hour. The exhaust gases are discharged to the ambient through a 1.5 m tall chimney. Figure 1 provides a schematic diagram of the test rig.

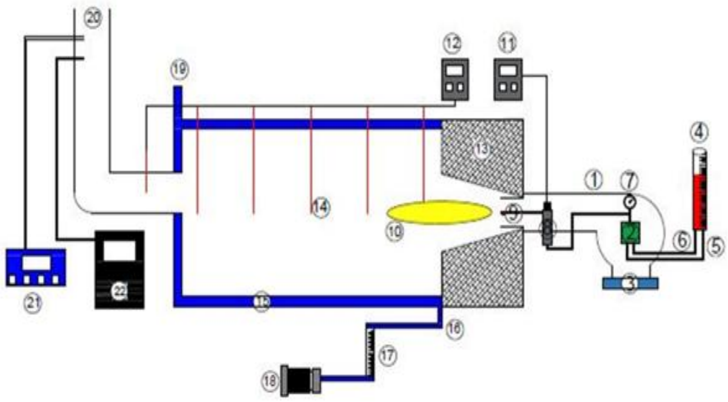

Fig. 1. The schematic diagram of the test rig.

(1) Burner; (2) Fuel pump; (3) Air flow meter; (4) Fuel tank; (5) Fuel suction; (6) Bypass fuel; (7) Pressure gauge; (8) Fuel Heater; (9) Nozzle;(10) Flame; (11) Fuel Heater Control; (12); Thermometer; (13) Insulation block; (14) Thermocouple; (15) Cooling water; (16) Cooling water Inlet; (17) Water flow meter; (18) cooling water pump; (19) Cooling water outlet; (20) Chimney;(21) Gas analyser; (22) SmokeMeter.

2.2. Measurements of research variables

The following are the experimentally measured parameters:

2.2.1. Mass flow rate of cooling water

An analogue sensor was used to determine the amount of heat released during the cooling process, which in turn determined the amount of water effluent used in the combustion chamber cooling process.

2.2.2. Fuel consumption

A burette was a tiny fuel tank used for fuel consumption measurement. Moreover, a stopwatch was used Fuel consumption is determined by measuring the burette's decrease over a given period.

2.2.3. Air consumption

The mass of the air flowing was computed using the known area of the air duct, the air density, and the speed recorded by the sensor. A digital turbine air sensor was utilized to measure the velocity of the air consumed in the combustion process.

2.2.4. Temperatures

In addition to measuring the temperature of the fuel, air, and cooling water in the combustion chamber, a K-type thermocouple with a temperature range of 0 to 1300 degrees Celsius was also used to measure the temperature of the flame and hot gases in the chamber.

2.2.5. Exhaust gas emission

Smoke opacity meters are used to detect and measure the amount of light blocked in the smoke released by diesel engines. Smoke opacity meters, as illustrated in Fig. 2, calculate the optical properties of diesel smoke. The exhaust gas analyser type HG-550 used for the exhaust analyses is shown in Fig. 3, and its specifications are displayed in Table 1.

Fig. 2. Smoke opacity meter.

Fig. 3. Gases analyser.

Table 1. Specifications of the gases analyser HG-550.

Item	specification			
Measuring Item	HC, CO, CO_2, O_2, Nox, λ			
Measuring Method	HC, CO, CO_2 – NDIR (Non-Dispersive Infrared) O_2, Nox – Electro Chemical			
Measuring Range Resolution Display	HC	0-10000 ppm 1 ppm 5 Digit FND	CO	0,000-9,999% 0,001% 4 Digit FND
Measuring Range Resolution Display	CO_2	0-20% 0.01% 4 Digit FND	O2	0-25% 0.01% 4 Digit FND
Measuring Range Resolution Display	NOx	0-5000 PPM 1 ppm 4 Digit FND	λ	0.5-3.00 0.01% 4 Digit FND
Repeatability	Less than ± 2% FS			
Response Time	Within 10 seconds (more than 90%), O_2 Nox ≤ 20 sec			

2.3. Fuel preparation

2.3.1. Heavy-light diesel fuel preparation

HLD fuel, which was created by combining 50% heavy diesel and 50% light diesel in volumetric proportions, was utilized in the experiment. A test experiment was carried out to investigate the benefits of using diesel fuel in the combustion process. The results showed that the fuel consumption cost could be halved by combining 50% heavy and light diesel, as opposed to using only light diesel. However, one drawback of heavy diesel is its high viscosity. In order to improve combustion, the fuel was emulsified with water, and five A/F ratios of 20, 25, 30, 35, and 40 were used for each fuel sample. Table 2 shows the properties of heavy and light diesel fuel.

Table 2. Properties of fuel from the Iraqi Ministry of Oil's Doura refinery laboratories in Baghdad.

Properties	Unit	Light Diesel	Heavy Diesel
Density @ 15 °C	kg/l	0.85	0.92
Viscosity @ 40°C	Cst	2.2	33.8
Flash point	°C	68	>100
Pour point	°C	<-21	0
Sulphur	Wt.%	1	3.2
Calorific value (high)	kcal/kg	10950	10626.8

2.3.2. Heavy-light diesel emulsion preparation

Emulsion production requires distilled water, a burette, HLD fuel, and a mechanical agitator (homogenizer), as shown in Fig. 4. The necessary quantity of HLD was measured in the burette, and the homogenizer's container was filled. The volume of each surfactant (span-80, HLB equal 4.3) was determined and put into the homogenizer's container, as shown in Fig. 5. The same protocol was applied to water. Lastly, the container is put under a mechanical agitator that is set to 30,000 rpm for ten minutes in order to thoroughly mix the mixture. After that, the resulting emulsion's stability was evaluated; Table 3 shows the results. The HLD fuel and distilled water were combined with Span-80 (1% of the final emulsion volume) to produce water/fuel emulsions at varying water-to-fuel (W/HLD) (vol./vol.) percentages of 10%, 15%, and 20%. Table 4 displays the amounts of surfactant, water, and HLD. Figure 6 shows the emulsion samples that were prepared.

Fig. 4. Emulsifier mixer (homogenizer).

Fig. 5. The surfactant.

Table 3. Properties of HLD fuel and its emulsions.

Fuel	HLD	E 10%	E 15%	E 20%
Density (ρ_f) @ 15 C° (kg/l)	0.885	0.896	0.902	0.908
Low heating value (LHV)(kJ/kg)	42341.9	42204.6	42128.4	42052.2

Table 4. Emulsion contents of water.

(E) emulsion	E 10%	E 15%	E 20%
contents	89% HLD, 10% water, 1% span 80	84% HLD, 15% water, 1% span 80	79% HLD, 20% water, 1% span 80

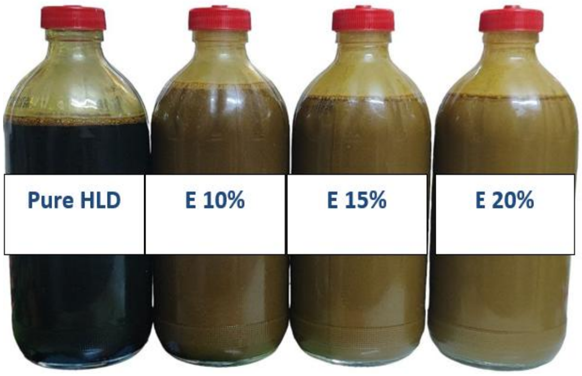

Fig. 6. The fuel emulsion samples.

3. Result and Discussion

The findings of this investigation are presented here in this section:

3.1. Comparison of fuel consumption rates for different emulsion types

Figure 7 shows that adding water to pure HLD gradually reduces the fuel consumption rate as the proportion of water in the mixture increases. This reduction in fuel consumption means that the stove requires less fuel with increased water content to achieve the necessary combustion. HLD emulsions with different water ratios of 10%, 15%, and 20% showed significant improvement in reducing the fuel consumption rate. This improvement makes the combustion process more efficient and environmentally friendly, resulting in greater fuel savings while achieving better combustion performance.

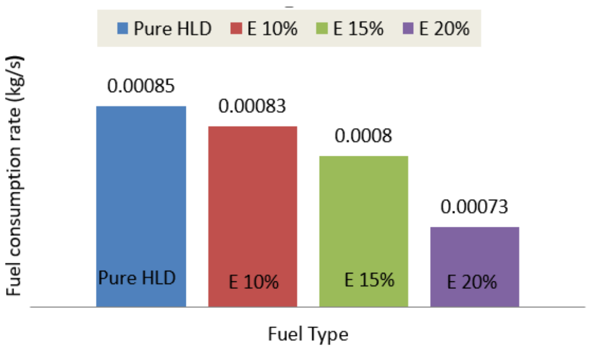

Fig. 7. Comparison of fuel consumption rates for different fuel types.

3.2. Exhaust gases temperature (EGT)

Figure 8 shows that EGT gradually increases and then steadily decreases as excess air increases for each type of fuel. This behaviour can be explained by the fact that the initial increase in air improves the combustion process and raises the exhaust gas temperature. However, when the air becomes excessive, it causes cooling of the gases, leading to a drop in temperature. Additionally, we notice from the figure that the higher the water content in the emulsion, the higher the EGT compared to pure HLD fuel. This increase is explained by the fact that the evaporation of water enhances combustion efficiency and improves fuel atomization. The following ratios explain this increase. For emulsions, 10%, 15%, and 20% water content, A/F ratios are 20, 25, and 30. For emulsions 10, 15, and 20% water content, the A/F is 20, 25, and 30. In comparison to pure HLD, there is an increase in exhaust temperatures of 0.3%, 0.6%, and 0.9% for A/F of 35, and an increase of 0.15%, 0.3%, and 0.4% for A/F of 40.

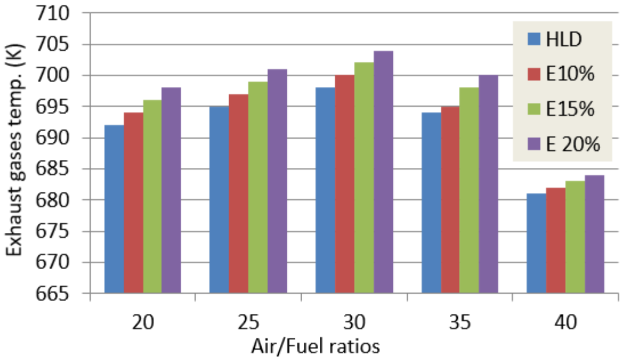

Fig. 8. Variation of the EGT with HLD and its emulsions at different A/F ratios.

3.3. Flame temperature

Figure 9 shows the measured flame temperatures at various A?F rations of the four tested emulsions. The flame temperature decreases with the increase in excess air. This decrease is explained by the fact that more excess air means more oxygen entering the combustion process, but this additional air does not participate in combustion and instead cools the flame. Similarly, the T_f decreases as the water content in the emulsion increases compared to pure HLD fuel. This behaviour can be explained by the fact that water absorbs heat to evaporate, and thus, with higher water content, the flame temperature decreases.

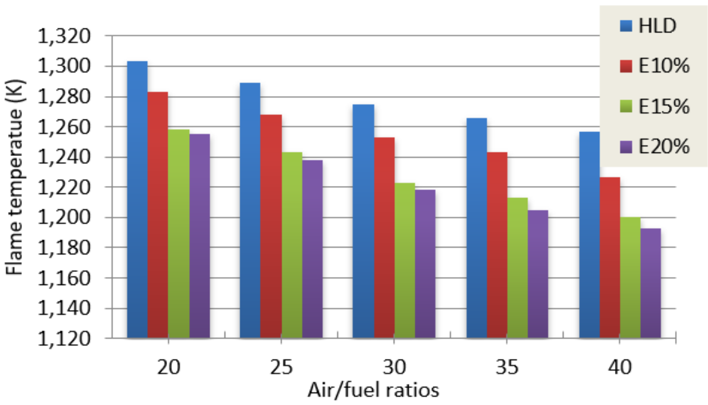

Fig. 9. Variation of the flame temperature with the HLD and its emulsions at different A/F ratios.

3.4. Carbon monoxide

Figure 10 shows that CO emissions increase with the rise in excess air for the same type of fuel. This increase is explained by the fact that excess air cools the combustion, leading to the formation of CO, which is not reduced to CO_2 due to the lack of high temperatures despite the availability of oxygen. The figure also shows a decrease in CO as the water content in the emulsion increases compared to pure HLD fuel. This decrease can be attributed to the fact that the presence of water improves combustion through the micro-explosion phenomenon, causing secondary atomization of the fuel and better mixing between the fuel and air.

When comparing E10% with Pure HLD at A/F (20, 25, 30, 35, 40), the percentage of CO formation decreased by 25%, 15%, 5%, 4%, and 1.4%, respectively. When comparing the results of E15% with Pure HLD, the percentage of CO formation decreased by 42%, 20%, 15%, 13%, and 10%, and when comparing the results of E20% with Pure HLD, the percentage of CO formation decreased by 50%, 31%, 26%, 17%, and 16%.

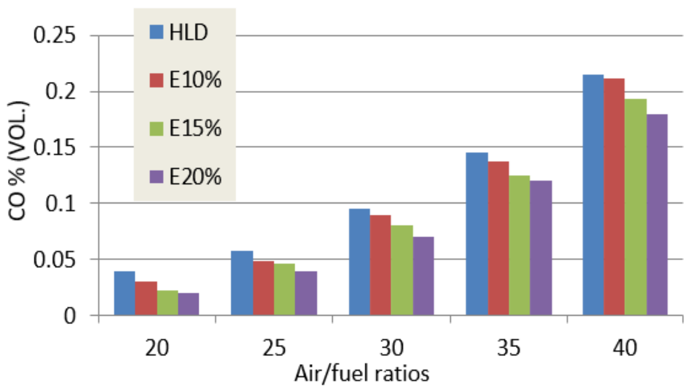

Fig. 10 . The change in CO emissions at various Air/Fuel ratios when using HLD and its emulsions.

3.5. Oxides of Nitrogen

Figure 11 illustrates how NOx changes when the HLD fuel and its emulsions are used at varying A/F ratios. The findings indicate that adding more excess air to the fuel mix reduces the amount of NOx that forms when using the same fuel. Increased airflow cools the flame and prevents thermal NOx from forming, which is the cause. The reduction of NOx is also a result of the water percentage in the emulsion. The latent water heat of evaporation is responsible for the observed percentage decreases in Nox. When comparing E10% with Pure HLD at A/F ratios of 20, 25, 30, 35, and 40, the percentage of NOx formation decreased by 24.5%, 25%, 38%, 33%, and 67%, respectively.

When comparing the results of E15% with Pure HLD, the percentage of Nox formation decreased by 40%, 45%, 61%, 73%, and 67%, and when comparing the results of E20% with Pure HLD, the percentage of Nox formation decreased by 58%, 70%, 76%, 73%, and 67% for A/F 20, 25, 30, 35, 40, respectively.

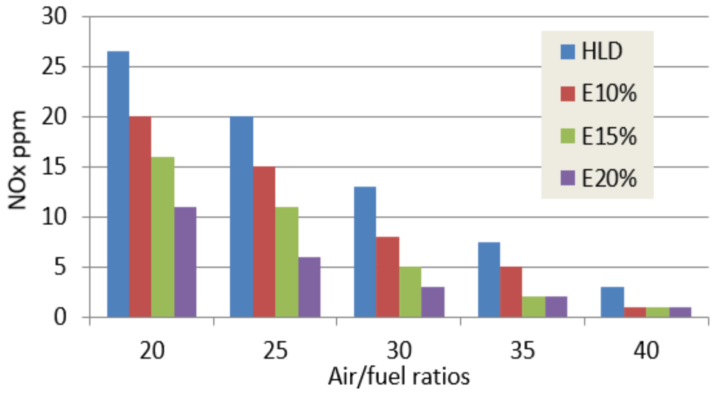

Fig. 11. The change in NOx emissions at various Air/Fuel ratios when using HLD and its emulsions.

3.6. Unburned hydrocarbon

The emissions of UHC are depicted in Fig. 12, and the increase in the percentages of water and A/F in the emulsion causes their quantities to be random. The ideal situation for this fuel's combustion, however, is represented by the exceptional circumstances in which the least amount of unburned hydrocarbon emissions is observed. E 15% has zero UHC emissions at A/F of 30. However, emulsions have 20% and 10% water content at A/F of 20 and 40, respectively. Finally, the best condition at HLD was an A/F of 40, as demonstrated in the results of Fig. 12.

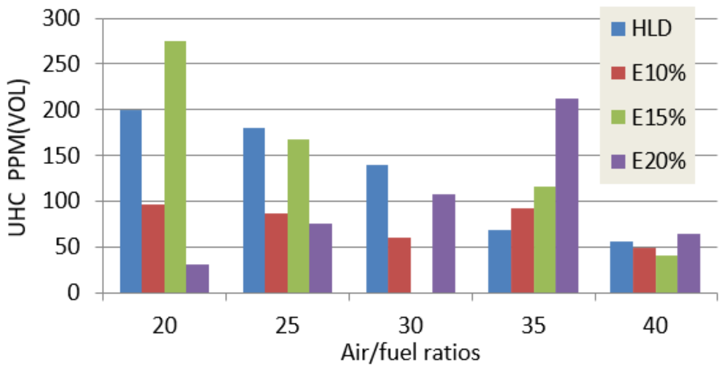

Fig. 12. The change in UHC emissions at various A ir/Fuel ratios when using HLD and its emulsions.

3.7. Smoke opacity

Figure 13 shows that the rate of smoke formation decreases with emulsified fuel compared to pure fuel due to the micro explosion resulting from the presence of water droplets inside the fuel. This explosion results in secondary atomization of the fuel, so the size of the fuel droplets decreases, which leads to the combustion of most of the carbon and also the higher excess air ratio A/F. The low smoke formation rate and the best condition for both pure fuel and its emulsions, 10%, 15%, and 20%, are at A/F of 40 and 35.

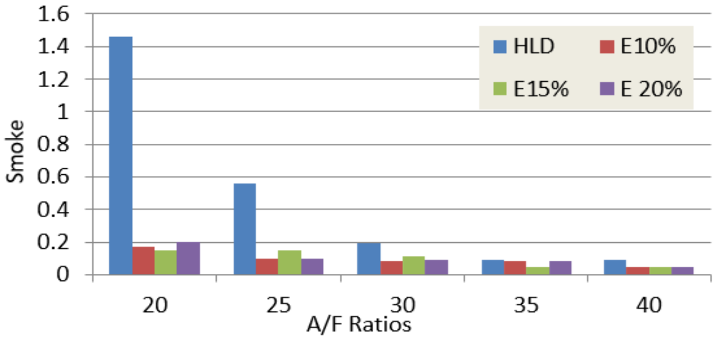

Fig. 13. The change in smoke emissions at various Air/Fuel ratios when using HLD and its emulsion.

3.8. Comparison with literature

Table 5 shows a comparison of the results of some previous studies. The table includes the type of fuel and the outcomes of each research.

Table 5. Comparison with research from literature.

Author & Ref.	Year	Used fuel	Used engine specifications	Findings
Razak et al. [23]	2021	Tested HFO samples with water contents of 0%, 5%, 10%, 20%, and 30% in mass.	A lab-scale burner with an air-blast nozzle and swirling airflow.	Reduced SOx, NOx, and particulate matter emissions
Li et al. [24]	2014	Heavy oil emulsion	boiler furnace	Increasing the η_{th} and reduced Nox, CO
Habib et al. [25]	2010	Jet A, soy methyl ester, canola methyl ester	gas turbine engine	increasing the η_{th} and reducing Nox and CO
Hsuan et al. [26]	2019	HFO with a (20 vol%) content of water	manufacturing boiler	Decreased NOX and rate of fuel consumption
Soulayman and El-Khatib [27]	2020	heavy oil—which is composed of 92% HFO and 8% water	boiler	raise the boiler efficacy and reduce the fuel consumption.
Lee et al. [28]	2021	Emulsified fuels were prepared and produced by blending 0%, 5%, 15%, and 25% water with Bunker C oil	applied to an actual marine boiler	NOx decreased by up to 31.41%.
Pei et al. [29]	2021	Malaysian Diesel grade 2 (D2M) labelled as D2, surfactant-added W/D and non-surfactant W/D. Both tested emulsion fuels contained 5%, 10% and 15% vol. water.	industrial burner	Compared to D2, non-surfactant W/D reduced fuel consumption, NOx, PM, CO, and HC emissions by up to 17%, 53%, 34%, 24% and 44%, respectively.
Saleh [30]	2024	used heavy diesel fuel, emulsifying it to three percentages: 5, 10, and 20%.	burner and combustion chamber	increasing the η_{th} and reducing Nox and CO
The current study	2024	Mixing heavy diesel and light diesel and emulsion it.	industrial burner and combustion chamber	reduced Nox, CO, fuel consumption

4. Conclusions

We conducted an experimental study on the effect of HLD fuel reversal (a 50/50 mixture of heavy diesel and light diesel) by 10%, 15%, and 20% volumes, and it was tested in the burner, noting important results.

- As the water content of the emulsion increased, the flame temperature decreased due to the absorption of combustion heat for water evaporation, thereby lowering the heat and aiding in the reduction of thermal NOx emissions.
- Smoke formation decreases with emulsion fuel compared to pure fuel due to micro-explosions caused by water droplets. Increasing the air-fuel ratio (A/F) further reduces smoke, with the optimal condition for both pure HLD fuel and emulsions (10%, 15%, and 20%) at A/F = 40.
- NOx formation decreases as the water content in the emulsion increases due to water's latent heat of evaporation, which absorbs heat, causing micro-explosions and lowering Tf, thereby reducing NOx.
- Practical results showed that adding water to pure HLD gradually reduces fuel consumption. Fuel consumption decreased by 2.4% with E10%, 5.9% with E15%, and 14% with E20% compared to pure HLD.

The current study demonstrated that water-in-fuel emulsions reduce emissions, especially NOx, by the most effective 20%. It also showed that adding water reduces fuel consumption, making it economically viable. The below investigations are recommended as upcoming projects for future work.

- Investigating the influence of employing emulsifiers for else fuels upon the performance of burner and the emissions.
- Explore new emulsification methods, such as ultrasonic homogenization, to enhance the stability and performance of water-in-fuel emulsions.
- Analysis of the effect of water on flame cooling using computational dynamic modelling techniques (CFD).

Nomenclature

LHV	Lower heating value of fuel, kJ/kg
$\mathring{m}_f$	Fuel consumption rate, kg/sec

Greek letters

ρ_f	Fuel density, kg/m^3

Abbreviations

A/F	The ratio between the mass of air to the mass of fuel
E	Emulsion
EGT	Exhaust gas temperature
HFO	Heavy fuel oil
HLD	Heavy-Light diesel
LFO	Light fuel oil
UHC	Unburned hydrocarbon
W/D	Water-in-Diesel
W/O	Water-in- Heavy fuel oil

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