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COMBUSTION AND EMISSIONS CHARACTERISTICS RESULTING FROM THE HEAVY OIL/WATER EMULSIONS BURNING IN AN INDUSTRIAL BURNER

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Abstract

The use of water-in-fuel emulsions improves combustion in engines. Increasing efficiency and reducing emissions are the goals of this improvement. With emulsions, Nitrogen Oxides, Carbon Dioxide, and particulates are reduced, while engine performance increases. Heavy oil is a byproduct of the crude oil distillation process and is neglected due to the difficulty of burning and the release of large amounts of soot from this process. Therefore, this research is designed to investigate the presence of water in the fuel will increase the amount of oxygen and hydrogen in it, which improves emissions specifications. The emulsions were prepared by adding surfactants to water and heavy and light Diesel fuel to improve their stability. An experimental pressure spray type in a combustion chamber burner was designed, fabricated, and used for combustion measurements. The total volume of heavy Diesel was diluted with distilled water at 5%, 10% and 20%, respectively. The results showed a 15% decrease in emulsion flame temperature than Diesel. Adding 10% water to the incinerator increased its thermal efficiency by 7.5%, and adding 20% water to the emulsion increased it by 14%. Compared to pure Diesel, a 20% water emulsion reduces NOx emissions by 50%. For the same emulsion, CO emissions decreased by 15%.

Keywords: Burner performance, Flame temperature, Industrial burner, Thermal efficiency, Water-in-Diesel.

1. Introduction

Crude oil distillation produces light gases and hydrocarbons that rise to the top of the capture tower. Due to their high Hydrogen-to-Carbon content, these hydrocarbons produce high energy and are more expensive. Hydrocarbons rich in carbon and low in hydrogen remain in the lower part of the distillation tower. Compared to their predecessors, these hydrocarbons are much cheaper. Heavy fuel oil (HFO) is one of these hydrocarbons [1, 2]. HFO is economically attractive due to its low cost, availability, and high energy density. This fuel is commonly used to power marine engines, fire industrial blast furnaces, and make electricity in utility boilers [3]. HFO has high viscosity, molecular weight, and high asphalt content [4]. The large size of the particles in this fuel prevents them from completely evaporating, so incomplete combustion occurs, and there is a high level of particulate matter in the exhaust [5]. As well as ash from unburned hydrocarbons, unburned hydrocarbons from the combustion process contain vanadium, sodium, and other minerals. Nitrogen Oxides and sulphur oxides are produced by burning HFO [6, 7].

A successful combustion process depends on the size and distance of the droplets travelling through the burner chamber [8]. Droplets must, therefore, be small enough to vaporize quickly. The droplet size must, however, be large enough to penetrate deeply into the combustion chamber [9]. It is optimal to control droplet size to achieve desired combustion conditions. Droplets in the combustion chamber travel a shorter distance when the viscosity of the fuel increases [10, 11]. In studies conducted by Chaichan et al. [12] and Fayad et al. [13], ethanol and methanol added to Diesel reduced viscosity and improved combustion. However, higher alcohols (butanol and propanol) increased the viscosity of its blends with Diesel [14, 15]. As a method for improving combustion, both [16, 17] recommended adding water to fuel oil. Through the addition of water, the flame temperature is lowered, reducing NOx emissions [18]. An emulsified fuel is the most common method of adding water to fuel oil.

A surfactant is added to the mixture to disperse the water droplets in the liquid fuel and form an emulsion [19]. Emulsion fuels are milky white fuels. As the emulsion droplets warm up in the combustion chamber due to the high temperature, the emulsion droplets evaporate and split into smaller droplets in a process called micro explosion [20, 21]. In the second stage of dissolution, emulsion droplets enter the high-temperature combustion chamber and explode, starting at the spray nozzle. After exploding into small droplets (such as secondary atomization), the droplets evaporate rapidly, mix with air over time, and then burn effectively [22, 23]. This micro-explosion process improves combustible mixture composition and combustion efficiency. Emulsified fuels also absorb heat, lowering the flame temperature and preventing the formation of Nitrogen Oxide, which requires high temperatures [24].

A possible improvement of the petroleum-derived fuels characteristics is the use of nanoadditives that complement the refining methods and provide sufficient opportunities to influence the hydrocarbon fuel characteristics. Magaril et al. [25] developed and studied the influence of multifunctional surface-active nano-additive on the petrol characteristics, engine performance, and environmental impact. The measurement results confirmed the effective reduction of the surface tension of gasoline at the contact surface with air, which resulted in improving the mixture formation in the combustion chamber. In addition, the saturated vapor pressure was significantly decreased, which dramatically reduced the evaporation losses and air pollution by light hydrocarbons emissions. To study the behaviour of fuel aerosols in a hot environment, Ismail et al. [26] used a fine syringe needle to inject fuel aerosols. A specially designed image processing technique was used to extract the size distributions of the dispersed droplets. The injection pressure was changed by 10% vol/v water content, and samples were photographed using a digital microscope. A reduction in droplet size led to a delay in atomization due to the injection pressure affecting secondary atomization.

Using a microchannel emulsifier and Sorbitan Sesquioleate as a surfactant, Melo-Espinosa et al. [27] studied the presence of micro-explosions and blowing into the emulsified fuel. They synthesized and analysed a set of stable dispersed systems in terms of optical properties and droplet size. Increasing the amount of water in the emulsion increased its viscosity. It was found that all emulsion fuels have jetting, but only surfactant-free emulsions showed microbursts. The ejection of many small droplets of emulsion was observed when smaller emulsion droplets were investigated. The size of water droplets, water percentage, and emulsion droplet size were all correlated with blowing, microbursts, and emulsion droplet size.

An emulsion of W/D was used in place of ultra-low sulphur Diesel (ULSD) in Dhahad et al. [28] tests. Under the same operating conditions, both fuels were tested for their performance and engine pollution. As a result of using emulsions, the combustion temperature in the chamber decreased, and fuel consumption increased. Nitrogen Oxides, PM emissions, and smoke decreased as hydrocarbon concentrations increased.

Zhu et al. [29] studied alcohol-based emulsified fuel using ethanol, biodiesel, and water to reduce fossil fuel consumption in internal combustion engines. The fuel's micro-explosion properties were further assessed using kinetic metrics, including micro-explosion delay, mean interfacial tension, bubble number, and mean micro-explosion intensity. In the study, the proposed metrics proved to be appropriate, and the mean micro-explosion intensity of the fuel increased with higher temperatures.

A fire-tube boiler was used in an industrial setting by Soulayman and El-Khatib [30] to test heavy fuel oil and its emulsion with water. The emulsion with 8% water content was observed to have the smallest, most uniform droplets following a stability test. Emulsion reduced fuel consumption by 12.99% and increased boiler efficiency. To meet the daily requirements of a fire tube boiler or a water tube boiler, Alaa et al. [31] designed, built, and tested a customized homogenizer to create a water/heavy fuel oil (W/HFO) emulsion with varying water levels. W/HFO emulsions with 8% water content were used instead of HFO in a fire tube boiler and reduced consumption by 13.56%. W/HFO emulsions with a higher water content had increased equivalent heat values, which are the net calorific values of the emulsion divided by the HFO content. In an industrial burner, Razak et al. [32] compared Malaysian Diesel Grade 2 (D2) and W/D emulsion fuels with water levels of 5%, 10%, and 15%. The higher flame temperature appeared to be generated by E5, while the fuel usage was lower for the W/D emulsion fuels than for D2. Increasing fan dampers increased NOx emissions, whereas decreasing fan dampers decreased CO and HC emissions.

The combustion system of a jet Diesel engine was enhanced by Liu et al. [33] to enable efficient and clean combustion under high load conditions in heavy-duty Diesel engines. Following the optimization process, there was a notable increase in the maximum internal heat release rate, rising from 86 J/° to 269 J/°, along with a boost in cumulative heat release by 112 J, thereby significantly amplifying the energy of the turbulence chamber jet.

Numerous researchers have extensively investigated, both practically and theoretically, the phenomenon of small explosions occurring in combustion chambers because of the presence of water mixed with heavy Diesel fuel. For instance, Sjögren [34] postulated that effective mixing of water in the fuel could lead to a minor explosion with just 2-3% water content, thus yielding the anticipated advantages. Conversely, in situations involving a coarse dispersion, higher water concentrations ranging from 12-15% are necessary to achieve comparable outcomes. Through the utilization of laser light scattering, Mattiello et al. [35] conducted a study focusing on the behaviour of emulsion droplets upon injection, specifically at water volumes of 10% and 20% v/v. Their findings indicated the occurrence of a minor explosion shortly after fuel injection, resulting in a reduced formation of soot. Additionally, Watanabe et al. [36] demonstrated that preceding the mini explosion, a rapid evaporation of up to 70% of water within the emulsion droplet took place. Observations by Kadota et al. [37] revealed that the initiation time of the microburst decreased with an increase in the boiling point of the primary fuel, elevated ambient pressures or temperatures, and higher water quantities.

In Iraq, thermal power plants, cement factories, and brick factories produce high levels of toxic emissions due to the incomplete combustion of heavy fuels. The used Iraqi heavy Diesel has a high content of sulphur. This fuel emits high NOx and PM concentrations into the air. Due to their high viscosity, density, and carbon-to-hydrogen ratio, this heavy Diesel fuel is difficult to atomize and burn, resulting in poor emissions like soot, carbon monoxide, and Nitrogen Oxides.

The current article aims to reduce both emissions and improve the combustion characteristics of heavy Diesel by water addition. There was no fuel saving with a new power plant that used water-emulsified crude oil. In this research, water-emulsified HFO has been produced at various compositions and investigated for its combustion in industrial burners, power plants boilers and furnaces. Fuel consumption was compared with and without water-emulsified HFO. Heavy fuel oil emissions will be reduced, combustion will be improved, and rotary pulsation will be applied to improve HFO combustion.

2. Materials and Methods

2.1. Experimental setup

Experiments were conducted using a burner and heavy Iraqi Diesel fuel and its emulsions in water to evaluate the performance and emissions of the burner. Iraqi Diesel was taken from Dora Refinery - Ministry of Oil. Figure 1 shows a photo of the burner used in experiments.

Figure 2 shows a schematic diagram of its parts, locations of the thermocouples, and other measuring devices. The combustion chamber unit includes the burning unit, which consists of a pressure atomizer, fuel supply system, air supply system, ignition system, and finally, the cooling unit. The current test involved the use of a cylindrical stainless-steel tube 1.5 mm thick, 440 mm inside diameter, and 1000 mm long from the combustion laboratory at the University of Technology, Baghdad. Water was supplied to the combustion process during the experiments via a water pump and was surrounded by a cylindrical galvanized steel jacket with a 3-cm gap between them. This shell acted as a water-cooling jacket and supplied the water needed to keep the combustion process steady.

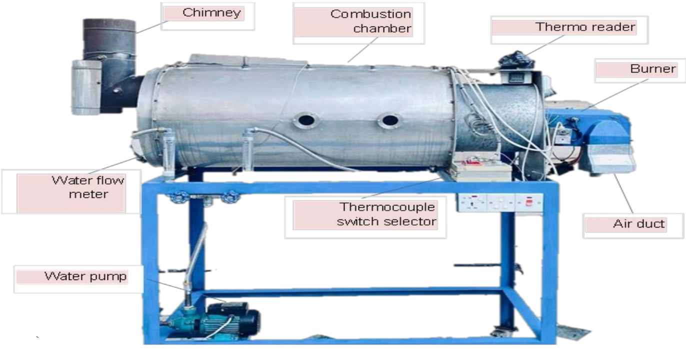
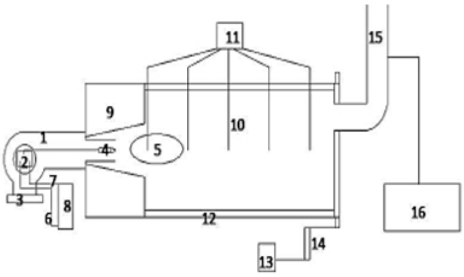


Fig. 1. Helical gear layout adopted in the simulation.



1	Burner	7	Bypass fuel	12	Cooling water
2	Fuel pump	8	Fuel tank	13	Water pump
3	Air flow meter	9	Insulation block	14	Water flow meter
4	Nozzle	10	Thermocouples	15	Chimney
5	Flame	11	Thermometer	16	Gas analyser
6	Fuel suction				

Fig. 2. A schematic diagram of the burner and combustion chamber used in the tests.

The burner also had a 300 mm side shaped like a cone surrounded by a thermal block (heat insulator). In addition to its high thermal conductivity, high melting point, and corrosion/rust resistance, stainless steel was selected for its high thermal conductivity. Five holes were made in uniform intervals of 230 mm along the combustion chamber to measure the flame temperature, as well as a hole in the insulating block. Type-K thermocouples and a single-channel digital thermometer with a 20-channel selector switch have been used to measure the temperatures. Furthermore, there was a 1500 mm chimney at the top of the combustion chamber with four symmetrical holes of 50 mm in diameter on both sides to allow insertion of the gas analyser probe.

The atomization of fuels can be accomplished by steam atomization for heavy fuels or air atomization for light fuels. In comparison with pressure atomizers, they produce a finer mist, improve air-fuel mixing, and improve combustion efficiency [38]. Pressure atomizers were used in factories and laboratories in the local area for their ease of operation. These factories included cement factories, asphalt factories, brick factories, gypsum factories, and kilns of medium size.

The fuel spray nozzle placed in the middle of fixed fins in the air duct swirls the air to increase air-fuel mixing in the vaporizer because of the high oil pressure provided by the oil pump. Different nozzle diameters and angles were used, and finally, a nozzle with a diameter of 0.2 mm and a 45-degree spray angle was chosen due to its suitability for high-pressure fuel consumption and good atomization efficiency. Among the components of the fuel supply system was a Danfoss type gear pump connected to the electric motor in the same shaft, with three ports on it. Fuel is taken in on the first port, pressure is applied on the second port, and bypass is applied on the third port. Through a screw, fuel consumption can be adjusted according to pump pressure. Fuel viscosity and density determine the pump's pressure, which ranges from 20 to 25 bars. Rotating wheels in spiral chambers act as air blowers. An electric motor is connected to it on the other side by a shaft. The air is drawn through a cylindrical tube 100 mm in diameter that contains a velocity gauge, which is described in more detail in section 2.4.

An air-fuel mixture is generated by forcing air through a 400 mm long conduit and directing it along the same axis as the fuel injector. Located in the neck of the nozzle, the electrodes of the ignition receive an electric spark from an electrical transformer within the burner body, increasing the voltage from 220 volts to 12 kV. In addition to the spark being generated by the pumping of fuel, the ignition converter is deactivated now the burner, i.e., combustion, is started, where a photo sensor detects the light from the flame and switches it off. A divided casing surrounds the combustion chamber, including two separate chambers for walls and bases. As a result, the chamber will be cooled more efficiently. Flow meters and temperature sensors are installed in each branch to control water flow and temperature. In the section on measuring devices, these measuring instruments are discussed in more detail. Pumps that supply water to both branches can pump 25 litres per minute.

2.2. Materials

A byproduct of oil refineries is heavy fuel oil, which is produced through distillation and cracking. In addition to kerosene, Diesel, and other components, it is produced in large quantities by distillation under atmospheric pressure. These residual materials were separated by vacuum distillation to take advantage of them. Due to their viscosity, density, and carbon-to-hydrogen ratio, these components are difficult to atomize and burn, resulting in poor emissions like soot, carbon monoxide, and Nitrogen Oxides. Distillation towers in the public sector produce heavy fuel oil rich in derivatives such as kerosene and Diesel. A high-wax Diesel is the most important derivative separated by vacuum distillation towers in the private sector. It is more difficult to atomize and burn due to its higher viscosity and density. This lower-cost alternative to heavy fuel oil contains high amounts of lubricating grease, which is a product of heavy fuel oil distillation, and a high level of heat, as shown in Table 1. The fuel sample properties were examined in the analysis division of the Doura Refinery laboratories in Baghdad of the Iraqi Ministry of Oil.

Table 1. Mesh independence criteria.

Properties	Unit	Light Diesel	Heavy Diesel	HFO
Density @ 15 °C	kg/L	0.824	0.9184	0.97
Viscosity @ 40 °C	Cst	2.2	33.8	220
Flash point	C°	68	>100	>100
Pour point	C°	< -21	0	+3
Sulphur	Wt.%	1	3.2	4.5
Calorific value (high)	kcal/kg	10950	10626.8	10420

2.3. Emulsion preparation

Emulsions are produced using a homogenizer, heavy Diesel, and distilled water. Diesel must be placed in the burette, and Span-80 (4.3 HLB) surfactant must be placed in the homogenizer container. Span 80 surfactant (Sorbian monooleate) with chemical formula C24H44O6 was used in the current study. Water/fuel emulsions were made by adding water to fuel at ratios of 5%, 10%, and 20% by adding 1.0% of Span-80 emulsion volume to diluted water and/or Diesel. The quantities of each component listed in Table 2 are required for this process. Figure 2 shows samples of the tested emulsions. The next step is to fill the container with distilled water in the same manner. For 5 to 10 minutes, the container is placed beneath a mechanical agitator at 20000 rpm to completely mix the mixture.

Table 2. Water dosages in W/LD and W/HD emulsions.

Code	W/LD emulsion
W/HD 5%	95% light Diesel, 4% water, 1% span 80
W/HD 10%	90% light Diesel, 9% water, 1% span 80
W/HD 20%	80% light Diesel, 19% water, 1% span 80

However, the prepared samples of emulsions have been characterized in the Dora refinery in Baghdad. The characterization results are shown in Table 3. It is important to examine the data in Table 3 to determine how stable the resulting emulsion will be.

Table 3. Measured properties of W/D emulsions.

Fuel	Density @ 15 C° (kg/l)	Low heat value (kJ/kg)
HD	0.9184	41890
W/HD 5%	0.924	39627.94
W/HD 10%	0.928	37365.88
W/HD 20%	0.936	32925.54

Samples of the produced emulsions, shown in Fig. 3, were kept and monitored to determine their stability and non-separation. The prepared emulsions have proven to be stable for more than 120 hours. The separation between water and fuel begins partially for two hours but then accelerates to complete separation within 6 hours. Then, it was mixed again to ensure a complete emulsion.

2.4. Instrumentations

In the experimental investigations, many parameters were measured. All the measuring devices were calibrated, and their accuracy was evaluated. Each part of the engine temperature was measured using a thermocouple K-Type and a single-channel digital reader with a 20-channel selector switch. The engine was equipped with 12 temperature sensors: seven for flames and hot gases, one in the core of the flame, five along the combustion chamber, one at the outlet of the combustion chamber, and one at the chimney outlet. The cooling water temperature was measured using three thermocouples. Fuel injection temperature and air injection temperature were measured using one thermocouple. To measure the airflow rate, a turbine sensor was used in conjunction with a digital reader that displayed air velocity in a 10 cm-diameter duct, and the air mass flow rate was determined using Eq. (1).

$$\dot{m}_a = V_a \times A \times \rho_a \quad (1)$$

Fig. 3. Samples of the Tested emulsions.

The fuel consumption of the engine was measured using a glass tube. It has a marking on the surface that indicates its volume is 1000 ml. A stopwatch was used to measure the consumption time of such a large amount of fuel. The fuel consumption rate was calculated using Eq. (2)

$$m_f = \frac{\rho_f \times v_f}{t} \tag{2}$$

Through two valves, a rotameter measured the cooling water flow rate and controlled the flow rate through two scales. The volumetric flow rate is measured by the rotameter and converted to mass flow. Exhaust gas emissions were measured using burner emission analysers type HG-550. The instrument measures NOx, CO_2, CO, O_2, and UHC gases. By installing a sensor in the exhaust chimney, a sensor gathers these gases from the continuous system exhaust pipe. The engine emission measurement device measures UHC, CO, and CO_2 content in exhaust gases by using a unique dispersion infrared analysis method in a sample cell with an infrared sensor. In addition, it assesses O_2 and NOx using electrochemistry measurements. There are four main components in the system: a vacuum pump, a sample cell, a preamp, and a light source. To determine the concentration of the emission gas, the sample cell absorbs its specific wavelengths. By passing through the sample cell and reaching the detector (infrared sensor), IR rays are emitted from the light source.

The following calculations are used to evaluate the system efficiency. The thermal efficiency of external combustion devices (burners) was calculated based on the equations below since the performance of these devices is evaluated through emissions and thermal efficiency.

$$\eta_{th} = \frac{Q_{exit} + Q_{water} + Q_{loss}}{Q_{in}} \tag{3}$$

where all heat values are in kW.

$$Q_{exit} = \dot{m}_{mix} \times \ Cp_{hot\ gas}\, C_P \times \Delta T \tag{4}$$

$$Q_{water} = \dot{m}_w \times C_P \times \Delta T \tag{5}$$

$$Q_{loss} = A \times h \times \Delta T \tag{6}$$

$$Q_{in} = \dot{m}_{fuel} \times LHV \tag{7}$$

2.5. Test procedure

For the first five minutes of the experiment, the burner warmed the combustion chamber until a steady state was reached. As a next step, an air-fuel combustion ratio was applied to each fuel sample at a fixed rate of fuel consumption. Flame and hot gas temperatures were measured in the combustion chamber and at their exit, as well as the cooling water flow rate and temperature before and after cooling. Also, an exhaust gas analyser reading was taken. A different air-fuel ratio was then used for each fuel sample, with air-fuel ratios ranging from 20, 25, 30, 35, and 40. Four fuel samples were analysed: heavy Diesel, emulsions of 5%, 10%, and 20% water/heavy oil. For three minutes, the cooling water flowed through the combustion chamber to cool the burners and gas analysers.

2.6. Uncertainty analysis

To determine the uncertainty of practical experiments, the calibration results of all measuring devices were adopted to ensure that they do not differ from the real measurements. Uncertainty was calculated for performance parameters using the following recommended equation by Al-Kayiem et al. [39].

$$e_R = \left[\left(\frac{\partial R}{\partial V_1} e_1\right)^2 + \left(\frac{\partial R}{\partial V_2} e_2\right)^2 + \cdots + \left(\frac{\partial R}{\partial V_n} e_n\right)^2\right]^{0.5} \quad (8)$$

where e_R is the uncertainty in the measurements, R is the independent variable, e_i represents the uncertainty coefficient in variable n, while $\partial R/\partial V$ expresses the measurement sensitivity of one variable.

Table 4 presents the measurement tools used in the experiments and the uncertainty for each. The cumulative uncertainty result of the test devices was ±1.664, indicating a high level of accuracy.

Table 4. Measured properties of W/D emulsions.

Measured variable	Measuring Device	Uncertainty (%)
Temperature	Thermocouples	±0.340
Turbine sensor	Airflow measurement	±0.928
Fuel glass tube	Fuel flow measurement	±0.620
Rotameter	Cooling fluid flow measurement	±0.284
NOx, CO_2, CO, O_2, and UHC gases	Emission analysers (EGMA) type (HG-550)	±1.152

$$e_R = [(0.34)^2 + (0.928)^2 + (0.620)^2 + (0.284)^2 + (1.152)^2\ ]^{0.5} = 1.664$$

3. Results and Discussion

3.1. The effect of water dosage on the emulsion properties

Figure 4 shows that water affects two major properties of heavy Diesel: density and the lower calorific value. Water has a higher density than Diesel, so the density increases. Because water has no calorific value for combustion, the calorific value in the emulsion decreases as the water content increases. Water and Diesel are combined physically rather than chemically, so the process does not change the fuel's chemical properties. Nevertheless, some studies conclude that more water added to an emulsion increases the fuel's calorific value. They are based on an experimental equation that calculates the calorific value as a function of density, and as density increases, the calorific value increases [31].

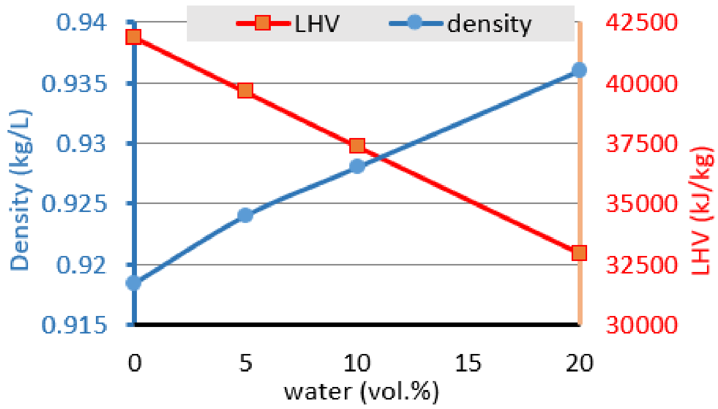


Fig. 4. Effect of added water percentage on lower heating value and density for Heavy Diesel.

3.2. Flame temperature

A comparison of the flame temperatures of the studied emulsions and heavy Diesel fuel is shown in Fig. 4. As the excess air ratio increases, the flame temperature decreases by below values compared to heavy Diesel.

- For 20 AF, temperatures were reduced by 1.3%, 1.8%, and 3.9% for 5%, 10%, and 20% water content, respectively.
- For 25 AF, temperatures were reduced by 1.4%, 3.4%, and 6% for 5%, 10%, and 20% water content, respectively.
- For 30 AF, temperatures were reduced by 2%, 4.5%, and 8.5% for 5%, 10%, and 20% water content, respectively.
- For 35 AF, temperatures were reduced by 2.7%, 5%, and 13.4% for 5%, 10%, and 20% water content, respectively.
- For 40 AF, temperatures were reduced by 3%, 7.7%, and 15.7% for 5%, 10%, and 20% water content, respectively.

Due to the presence of an abundance of air that cools the flame, when excess air is increased, the flame temperature decreases. When increasing the percentage of water in the emulsion, the flame temperature decreases because of the latent heat of water vaporization. By absorbing part of the combustion heat and releasing it as a flame retardant, the water reduces the flame temperature. The reduction in flame temperatures results in a reduction in NOx emissions formation.

3.3. Exhaust gas temperature

The exhaust gas temperature (EGT) changes as the excess air ratio increases in Fig. 6. In the presence of excess air, the temperature increases initially, then continuously decreases. Due to the abundance of air available for combustion, when the excess air is increased, the combustion will cool. Further, the fuel was fully burned, with the lowest level of unburnt hydrocarbons recorded, indicating a higher temperature. Temperatures drop when air is added to the combustion, cooling it. EGT increases with adding water to the emulsion, resulting in higher thermal efficiency. Combustion produces a higher amount of vapour due to the increased water mass. For emulsions of 5%, 10%, and 20%, EGT dropped between 0.3% and 1.2% for A/F ratios of 20, 25, 30, 35, and 40.

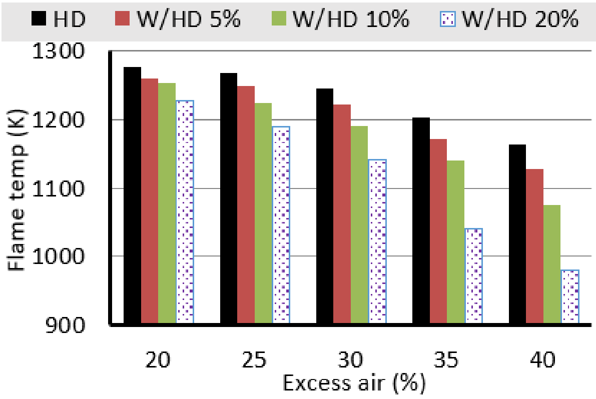


Fig. 5. The variation of flame temperatures with heavy Diesel and its emulsions at different excess air ratios.

3.4. Temperature distribution

In Figs. 7(a) to 7(d), distributions of temperatures are shown in a longitudinal direction by increasing excess air ratio when burning pure Diesel at different ratios, as well as for an emulsion at 5%, 10%, and 20%, respectively. As the concentration of atomized fuel increases near the nozzle and decreases away from it, the temperature shows a constant behaviour of decreasing with distance as the closer the nozzle is, the higher the concentration, and the farther away from it the lower the quantity. By evaporating water and removing part of the combustion heat for this purpose, these temperatures can also be reduced by increasing the percentage of water in the suspension.

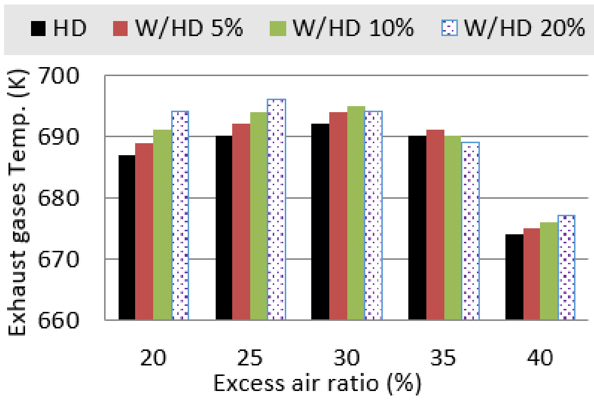
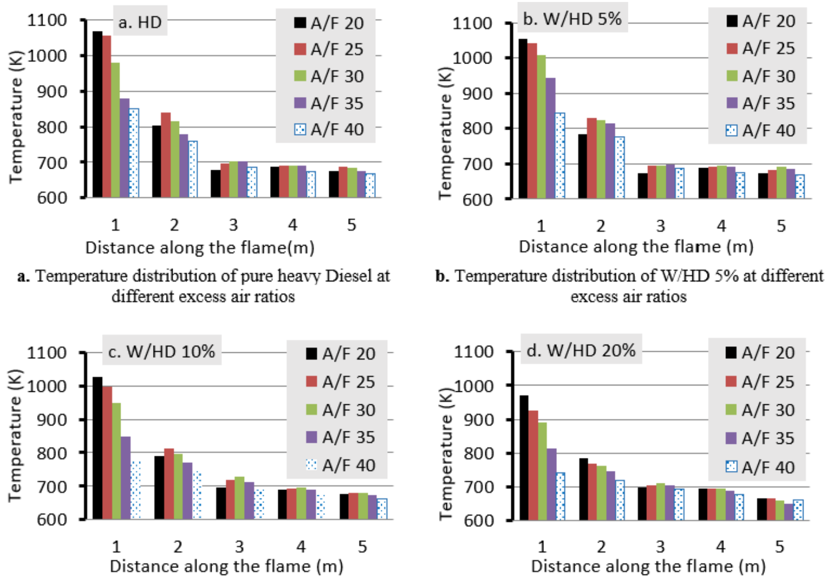


Fig. 6. The variation of EGT with heavy Diesel and its emulsions at different excess air ratios.



a. Temperature distribution of pure heavy Diesel at different excess air ratios

b. Temperature distribution of W/HD 5% at different excess air ratios

c. Temperature distribution of W/HD 10% at different excess air ratios

d. Temperature distribution of W/HD 20% at different excess air ratios

Fig. 7. Temperature distribution for the studied emulsions at variable excess air ratios in the longitudinal direction of the flame.

3.5. Emulsion emissions as a function of water content

3.5.1. NOx emissions

In Fig. 8(a), Nitrogen Oxide levels are shown for heavy Diesel and its emulsions at various air levels. For the same type of fuel, increasing the air-to-fuel ratio (increasing excess air) decreased NOx formation. To limit Nitrogen Oxide formation, it is necessary to increase the amount of air cooling the flame. By increasing the water percentage in the emulsion, Nitrogen Oxides are reduced. For heavy Diesel and its emulsions, the NOx concentration decreased as follows: A/F 20, 25, 30, 35, and 40 for emulsions of 5, 10, 20% water, the reduction rates were 20, 36, and 50%; 29.52 and 76%; and 36, 63, 90% and 80%, respectively, compared with pure Diesel. The water in the emulsion takes part of the heat generated in the combustion chamber, hence reducing the inner temperature and controlling the NOx formation.

3.5.2. UHC emissions

Figure 8(b) shows unburned hydrocarbon concentrations. Because of the increase in air/fuel ratios and the increase in water percentage in the emulsion, the HC concentrations are random. In certain conditions, however, fewer unburned hydrocarbons are emitted, which represents the optimum combustion condition for this fuel. For heavy Diesel and its studied emulsions, it has been found that the level of UHC emissions for pure Diesel and its emulsions 5, 10, and 20 is as low as possible (the HC levels were 8 ppm, 7 ppm, 10 ppm, and 40 ppm for excess air ratio of 25%, 30%, 35%, and 40%, respectively. This could be attributed to small explosions of emulsion droplets as the Diesel decomposes into smaller droplets, resulting in improved combustion and reduced unburned hydrocarbon emission. This result is what both references [40, 41] reached.

3.5.3. CO emissions

Figure 8(c) shows that carbon monoxide emissions increased with an increase in excess air for the same type of fuel. A decrease in air and dissolution of carbon dioxide result in the formation of carbon monoxide gas. Carbon monoxide emissions increase when temperatures drop below 1100 K. Due to excess air being used by the burner, carbon monoxide is formed relatively infrequently, not exceeding 0.25% of total emissions. Compared to Diesel, carbon monoxide emissions decrease when the proportion of water in an emulsion increases. The secondary decomposition resulting from the micro explosion is responsible for this, as compared to pure Diesel at excess AF of 20%, 25%, 30%, 35%, and 40%, carbon monoxide emissions for heavy Diesel emulsions of 5%, 10%, and 20% were reduced by 20%, 29%, and 41%; 16%, 25%, and 33%; 12%, 18.5%, and 25%; 8.2%, 8.3%, and 16%), and 4.5%, 9%, and 13.6%, respectively. This reduction can be attributed to excess air and oxygen liberated from micro-explosions as well as the suitable conditions to oxidize CO to CO_2.

3.5.4. CO_2 emissions

Carbon dioxide emissions are shown in Fig. 8(d). The CO_2 emissions decreased as the excess air ratio increased, which is quite normal since oxygen is abundant in the combustion chamber. Compared to pure Diesel, CO_2 emissions decrease as the proportion of water in the emulsion increases. However, this decrease is limited, and its effects are less than excess air. Evaporation of water results in an increase in water vapor, which decreases volumetric emissions. As compared to Diesel, heavy Diesel emulsions reduced carbon dioxide emissions by 2.5% to 11%.

3.6. Combustion efficiency

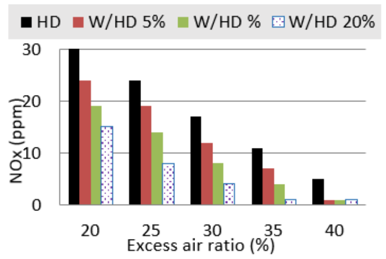
3.6.1. Effect of excess air ratios on the efficiency

Combustion efficiency is a measure of how much exhaust gas emissions are reduced, particularly carbon monoxide emissions. Combustion efficiency decreases as excessive air is introduced into the combustion process, as shown in Fig. 9. Carbon monoxide emissions are increased at higher rates of excessive air. The combustion efficiency increases when the water content in the fuel emulsion is higher than that of pure fuel. Using a 20% water emulsion, for instance, increases combustion efficiency by 1% over heavy Diesel.

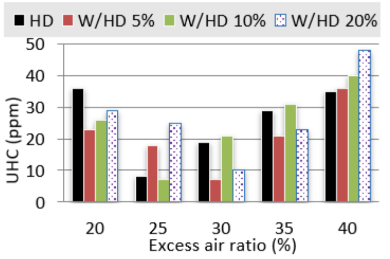
$$\eta_c = \frac{CO_2}{CO_2 + CO} \times 100 \quad (9)$$

3.6.2. Effect of water dosage in an emulsion on the thermal efficiency

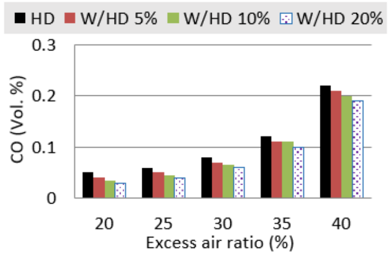
Based on Figs. 10 and 11, the thermal efficiency of the studied emulsions is influenced by the amount of air and water present. Thermal efficiency increases up to a certain level before declining as the amount of air used for combustion increases. As a result, the combustion chamber and exhaust gases are cooled, and efficiency is reduced by the greater mass of air entering the combustion chamber. When water is added to an emulsion, micro-explosions are produced, which result in a reduction in unburnt hydrocarbons. Water that turns into steam also increases the total mass, boosting combustion temperature and efficiency.



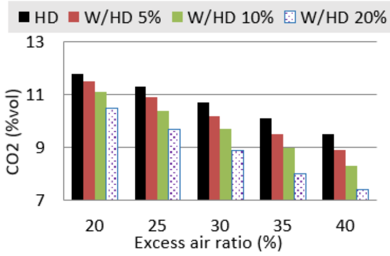
a. The variation of NOx emissions with heavy Diesel and its emulsions at different A/F



b. The variation of UHC emissions with heavy Diesel and its emulsions at different A/F



c. The variation of CO emissions with heavy Diesel and its emulsions at different A/F



d. The variation of CO2 emissions with heavy Diesel and its emulsions at different A/F

Fig. 8. Measured emulsions emissions levels at variable A/F ratios.

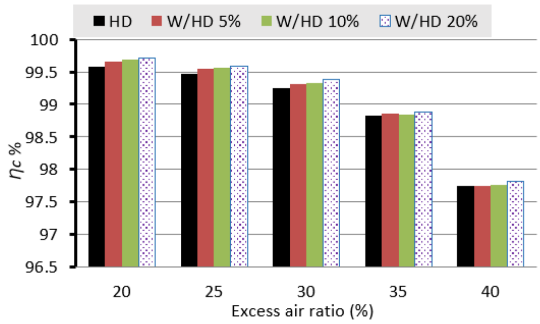


Fig. 9. The variation of combustion efficiency with heavy Diesel and its emulsions at different Excess air ratios.

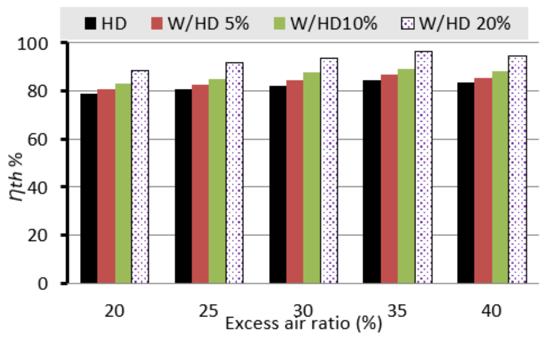


Fig. 10. The variation of thermal efficiency with heavy Diesel and its emulsions at different Excess air ratios.

Compared to heavy Diesel, emulsions of water at different Excess AF percentages of 20, 25, 30, 35, and 45 and water percentages of 5, 10, and 20 were 1.4%, 5.2%, and 11.5%; 2.5%, 5%, and 12%; 2.7%, 6.7%, and 13.8%; 2.7%, 5.2%, and 13.5%; and 2.6%, 5.4%, and 13.2%, respectively. Burning pure fuel with its emulsifier at 5%, 10%, and 20% water percentage results in the highest efficiency, as Fig. 11 depicts. A 2.8%, 5.2%, and 13.9% increase in efficiency is seen when the level of water in the emulsion is increased compared to pure heavy Diesel.

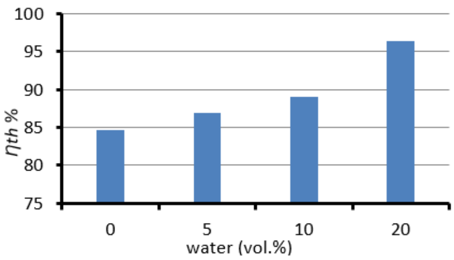


Fig. 11. Variation of thermal efficiency of heavy Diesel and its emulsions with water content.

4. Conclusions

Heavy Diesel is a cheap and widely used fuel in third-world countries, including Iraq. Despite its high sulphur content, this fuel emits significant environmental pollution. Consequently, this study proposed a practical alternative to the fuel, which is a mixture of heavy diesel fuel and water emulsions. These emulsions' performance and pollutants have been compared with those from heavy Diesel incinerators fuelled by these emulsions. Based on the study, the following conclusions were drawn:

- Emulsions derived from heavy Diesel fuel are a locally sourced fuel alternative. Combustion of this fuel is easier and more efficient than that of heavy fuel oil. A better combustion quality has been achieved through the emulsification process.
- The flame temperature of emulsion fuel with 20% water content is 15% lower than that of heavy pure Diesel. By reducing the flame temperature, the burner's efficiency and emissions are improved. When burning pure Diesel at a constant or high flame temperature, a significantly lower flame temperature is achieved.
- The performance and emissions of the combustion device are influenced by both the fuel quality and the amount of water in the emulsion. As a result of burning emulsion instead of pure Diesel, the burner's thermal efficiency increases by 12% when emulsion contains 20% water compared to heavy Diesel.
- Compared with heavy pure Diesel, fuel emulsions containing 20% water reduced Nitrogen Oxide emissions by more than half.
- Burning Diesel emulsion with 20% water content reduced the amount of carbon monoxide released into the atmosphere by 50% compared to burning pure Diesel.

The results show that reducing sulphur by adding water causes a decrease in pollutant concentrations and improved combustion, which justifies this trend in the future.

Nomenclature

A	Turbo sensor area, m^2
A_c	The external area of the combustion chamber, m^2
Cp	Specific heat of hot gases (kJ/kg·K)
h	Convection heat transfer coefficient, W/m^2·K
LHV	Lower heating value of fuel, kJ/kg
m_f	Fuel consumption rate, kg/sec
$\dot{m}_{mix}$	Amount of air and fuel mixture, kg/s
Q_{exit}	The amount of heat released in hot gases, kW
Q_{in}	The amount of heat released from the combustion of the fuel, kW
Q_{loss}	The amount of heat lost in the structure, kW
Q_{water}	The amount of heat released in the cooling water, kW
V_a	Average speed measured in the turbo sensor, m/s
v_f	Volume of fuel consumption, m^3

Greek letters

ΔT	Temperature difference between hot gases and the atmosphere, K, °C
η_c	Combustion efficiency, %
ρ_a	Air density, kg/m^3
ρ_f	Fuel density, kg/m^3

Abbreviations

EGT	Exhaust gas temperature
HOF	Heavy fuel oil
UHC	Unburned hydrocarbon
W/D	Water-in-Diesel
W/HFO	Water-in-heavy fuel oil emulsion

References

1. Wu, J. et al. (2023). Molecular characterization of non-polar sulphur compounds in the full boiling range crude oil fractions. *Fuel*, 338, 127323.
2. Pham, D.V.; Nguyen, N.T.; Kang, K.H.; Seo, P.W.; and Park, S. (2023). Study into the effects of the feedstock properties and stability on the catalytic hydrocracking of heavy oil. *Fuel*, 339, 127427.
3. Tariq, A.I.; and Saleh, A.M. (2023). An experimental investigation into the combustion properties, performance, emissions, and cost reduction of using heavy and light fuel oils. *Case Studies in Thermal Engineering*, 44, 102832.
4. Jameel, A.G.A.; Elbaz, A.M.; Emwas, A.-H.; Roberts, W.L.; and Sarathy, S.M. (2016). Calculation of average molecular parameters, functional groups, and a surrogate molecule for heavy fuel oils using 1H and 13C nuclear magnetic resonance spectroscopy. *Energy & Fuels*, 30(5), 3894-3905.
5. Moro, M.K.; dos Santos, F.D.; Folli, G.S.; Romao, W.; and Filgueiras, P.R. (2021). A review of chemometrics models to predict crude oil properties from nuclear magnetic resonance and infrared spectroscopy. *Fuel*, 303, 121283.

6. Jameel, A.G.A. et al. (2019). Characterization of de-asphalted heavy fuel oil using APPI (+) FT-ICR mass spectrometry and NMR spectroscopy. *Fuel*, 253, 950-963.
7. Fan, J. et al. (2022). Molecular characteristics of sulphur compounds in oxidative desulfurization for heavy fuel oil based on APPI FT-ICR MS analysis. *Catalysis Today*, 404, 262-268.
8. Chaichan, M.T. (2018). Combustion and emission characteristics of E85 and diesel blend in conventional diesel engine operating in PPCI mode. *Thermal Science and Engineering Progress*, 7, 45-53.
9. Zhang, Q. et al. (2022). Experimental study on ignition and combustion characteristics of biodiesel-butanol blends at different injection pressures. *Renewable and Sustainable Energy Reviews*, 160, 112289.
10. Ekaab, N.S.; Hamza, N.H.; and Chaichan, M.T. (2019). Performance and emitted pollutants assessment of diesel engine fuelled with biokerosene. *Case Studies in Thermal Engineering,* 13, 100381.
11. Dhahad, H.A.; Fayad, M.A.; Chaichan, M.T.; Jaber, A.A.; and Megaritis, T. (2021). Influence of fuel injection timing strategies on performance, combustion, emissions and particulate matter characteristics fuelled with rapeseed methyl ester in modern diesel engine. *Fuel*, 306, 121589.
12. Chaichan, M.T.; Ekab, N.S.; Fayad, M.A.; and Dhahad, H.A. (2022). PM and NOX emissions amelioration from the combustion of diesel/ethanol-methanol blends applying exhaust gas recirculation (EGR). *IOP Conference Series*: *Earth and Environmental Science*, 961(1), 012044.
13. Fayad, M.A.; Chaichan, M.T.; Dhahad, H.A.; Al-Amiery, A.A.; and Isahak, W.N.R.W. (2022). Reducing the effect of high sulphur content in diesel fuel on NOx emissions and PM characteristics using a PPCI mode engine and gasoline–diesel blends. *ACS Omega*, 7(42), 37328-37339.
14. Yousif, I.E.; and Saleh, A.M. (2023). Butanol-gasoline blends impact on performance and exhaust emissions of a four-stroke spark ignition engine. *Case Studies in Thermal Engineering*, 41, 102612.
15. Chaichan, M.T. et al. (2022). Ultralow sulphur diesel and rapeseed methyl ester fuel impact on performance, emitted regulated, unregulated, and nanoparticle pollutants. *ACS Omega*, 7(30), 26056-26075.
16. Won, J.; Baek, S.W.; Kim, H.; and Lee, H. (2019). The viscosity and combustion characteristics of single-droplet water-diesel emulsion. *Energies*, 12(10), 1963.
17. Wang, Z. et al. (2018). Effects of water content on evaporation and combustion characteristics of water emulsified diesel spray. *Applied Energy*, 226, 397-407.
18. Chaichan, M.T.; Kadhum, A.A.H.; and Al-Amiery, A.A. (2017). Novel technique for enhancement of diesel fuel: Impact of aqueous alumina nano-fluid on engine's performance and emissions. *Case Studies in Thermal Engineering*, 10, 611-620.
19. Zi, M.; Chen, D.; Wang, J.; Hu, P.; and Wu, G. (2019). Kinetic and rheological study of methane hydrate formation in water-in-oil emulsion: Effects of emulsion composition and silica sands. *Fuel*, 255, 115708.
20. Téré, D. et al. (2022). Evaporation and combustion of a drop of liquid fuel-A review. *Smart Grid and Renewable Energ*y, 13(2), 28-54.

21. Wang, Z. et al. (2022). Progress in experimental investigations on evaporation characteristics of a fuel droplet. *Fuel Processing Technology*, 231, 107243.
22. Wang, Z. et al. (2022). A new shift mechanism for micro-explosion of water-diesel emulsion droplets at different ambient temperatures. *Applied Energy*, 323, 119448.
23. Dhahad, H.A.; and Chaichan, M.T. (2020). The impact of adding nano-Al_2O_3 and nano-ZnO to Iraqi diesel fuel in terms of compression ignition engines' performance and emitted pollutants. *Thermal Science and Engineering Progress*, 18, 100535.
24. Doppalapudi, A.T.; Azad, A.K.; and Khan, M.M.K. (2023). Advanced strategies to reduce harmful nitrogen-oxide emissions from biodiesel fuelled engine. *Renewable and Sustainable Energy Reviews*, 174, 113123.
25. Magaril, E. et al. (2019). Investigation on the possibility of increasing the environmental safety and fuel efficiency of vehicles by means of gasoline nano-additive. *Sustainability*, 11(7), 2165.
26. Ismael, M.A. et al. (2018). Investigation of puffing and micro-explosion of water-in-diesel emulsion spray using shadow imaging. *Energies*, 11(9), 2281.
27. Melo-Espinosa, E.A. et al. (2018). Experimental investigation of emulsified fuels produced with a micro-channel emulsifier: Puffing and micro-explosion analyses. *Fuel*, 219, 320-330.
28. Dhahad, H.A.; Chaichan, M.T.; and Megaritis, T. (2019). Performance, regulated and unregulated exhaust emission of a stationary compression ignition engine fuelled by water-ULSD emulsion. *Energy*, 181, 1036-1050.
29. Zhu, J.; Li, R.; Wang, Z.; and Liu, S. (2021). Microexplosion kinetics of alcohol-based emulsified biodiesel droplets evaporated in high temperature. *Journal of Energy Engineering*, 147(6), 04021047.
30. Soulayman, S.; and El-Khatib, R. (2020). The effect of fuel emulsion on fuel saving in fire tube boilers of Tartous company for cement and construction materials. *Journal of Solar Energy Research Updates*, 7, 1-6.
31. Alaa, M.; Soulayman, S.; Abdelkarim, T.; and Walid, Z. (2021). Water/heavy fuel oil emulsion production, characterization and combustion. *International Journal of Renewable Energy Development*, 10(3), 597-605.
32. Razak, I.F.A. et al. (2020). Burner performance and emissions fuelled with water-indiesel emulsion fuel. *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences*, 65(1), 13-24.
33. Liu, Y.; Su, W.; Wu, B.; and Wang, J. (2024). The research and development of a jet disturbance combustion system for heavy-duty diesel engines. *Energies*, 17(5), 1065.
34. Sjögren, A. (1977). Burning of water-in-oil emulsions. *Symposium* (*International*) *on Combustion*, 16(1), 297-305.
35. Mattiello, M.; Cosmai, L.; Pistone, L.; Beretta, F.; and Massoli, P. (1992). Experimental evidence for microexplosions in water/fuel oil emulsion flames inferred by laser light scattering. *Symposium* (*International*) *on Combustion*, 24(1), 1573-1578.

36. Watanabe, H. et al. (2010). An experimental investigation of the breakup characteristics of secondary atomization of emulsified fuel droplet. *Energy*, 35(2), 806-813.
37. Kadota, T.; Tanaka, H.; Segawa, D.; Nakaya, S.; and Yamasaki, H. (2007). Microexplosion of an emulsion droplet during Leidenfrost burning. *Proceedings of the Combustion Institute*, 31(2), 2125-2131.
38. Gold, M. et al. (2019). Simulation and measurement of transient fluid phenomena within diesel injection. *SAE International Journal of Advances and Current Practices in Mobility*, 1(2019-01-0066), 291-305.
39. Al-Kayiem, H.H.; Tukkee, A.M.; and See, Y.K. (2024). Experimental assessment of a solar vortex engine integrated with sensible TES at different collector configurations. *Renewable Energy*, 227, 120539.
40. Mukhtar, M.N.A. et al. (2019). Tri-fuel emulsion with secondary atomization attributes for greener diesel engine-A critical review. *Renewable and Sustainable Energy Reviews*, 111, 490-506.
41. Mosadegh, S. (2024). *Influence of atomization on single and multi-droplet combustion of Diesel, biodiesel, and ethanol doped with graphene oxide*. PhD Thesis, Applied Science, Faculty of Engineering, University of British Columbia.