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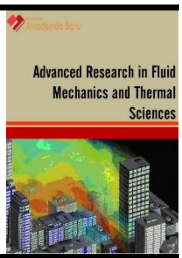

Burner Performance and Emissions Fuelled with Water-in-Diesel Emulsion Fuel

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Ili Fatimah Abd Razak[1], Wira Jazair Yahya[1,*], Ahmad Muhsin Ithnin[1], Muhammad Afiq Haikal Norazman[1], Muhammad Ahmar Zuber[1], Nur Atiqah Ramlan[1]

[1] Malaysia-Japan International Institute of Technology, Universiti Teknologi Malaysia, Jalan Sultan Yahya Petra, 54100 Kuala Lumpur, Malaysia

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ABSTRACT

The combustion of low-quality fossil fuels by industrial burners release toxic exhaust emissions such as NO_x, CO and HC. Introduction of water in combustion have been proven to improve combustion efficiency and reduce toxic emissions in several studies. One of the methods of water introduction in combustion is water emulsified fuel. In present study, the combustion of Malaysian Diesel grade 2 (D2), and Water-in-Diesel (W/D) emulsion fuels with 5%, 10% and 15% water volume (labelled as E5, E10 and E15, respectively, using an industrial burner was investigated. The aim of the study is to measure the fuel consumption, flame temperature, and exhaust emissions of the industrial burner fuelled with the test fuels to find a suitable setting for an optimum combustion of the W/D emulsion fuels. It is found that the flame temperature of all the tested fuels were the highest at fan damper 2 setting. Additionally, the combustion of E5 showed the highest flame temperature compared to other tested fuels. The fuel consumption for all W/D emulsion fuels were lower than that of D2. The NOx emission of the tested fuels increased with the increase of fan damper number, whereas the CO and HC emission showed otherwise.

1. Introduction

Agriculture, mass transportations and industries are among the activities that consume a large amount of fossil fuel. To reduce the production cost, they inclined to consume low quality fuel. However, the combustion of low-quality fuels exhaust toxic emissions such as Nitrogen Oxides (NO_x) and Carbon Monoxide (CO) which are harmful to public health and environment as well. The stricter regulation set up by Malaysian Department of Environment (DOE) on exhaust emissions is pushing industries to find better alternatives to control toxic emissions [1]. There are several methods to control toxic emissions such as adding additives in the combustion [2–4] or blending the low quality fuel with a higher grade fuel [5]. There is also an option to replace fossil fuels with biodiesel [6], but the high production cost these methods still makes them unfeasible to be utilized in industries.

* *Corresponding author.*
E-mail address: wira@utm.my (Wira Jazair Yahya)

Introduction of water in combustion is one of the methods that received a lot of research interest as a countermeasure for the increase in air pollution contributed by the combustion of low-quality oil and diesel fuel. The addition of water in combustion can be carried out by water or steam injection, or by emulsifying water in liquid fuels such as Water-in-Diesel (W/D) emulsion fuel. An emulsion is a mixture of two or more immiscible liquids, formed when one liquid exists as a dispersed droplet in the other liquid known as the continuous phase [7]. It is also one of the promising method that can improve combustion efficiency, and reduce NO_x and particulate matter emissions [8–13]. The reduction of these emissions and improvement in combustion can be explained by the occurrence of micro-explosion phenomenon in the combustion [14]. Furthermore, several studies conducted observed that the increase in water amount in water emulsified fuels decreased NO_x emission [8,15]. Basha and Anand also observed a reduction in peak flame temperature by the increase of water amount in water emulsified fuel leads to the reduction of NO_x emission [16]. The increase of water content in water emulsified fuels was also observed to reduce CO emission [17]. In addition, Chelemuge *et al.,* [18] reported that the NO_x and CO emissions were reduced with the decrease of excess air ration in the combustion.

The application of W/D fuel in diesel engine had been widely studied, however this is not the case for industrial burner. The purpose of this study is to find the optimum condition for the combustion of W/D emulsion fuel through variation in inlet air in the burner and water percentages in W/D emulsion fuels. In present study, the combustion performance and exhaust emissions by an industrial burner fuelled with Malaysian Grade 2 diesel (D2), W/D emulsion fuels with 5, 10 and 15 % water content, labelled as E5 and E10, respectively was investigated. The W/D emulsion fuels was stabilised with 1% of Span 80 surfactant.

2. Methodology

2.1 Industrial Burner

The investigation was conducted at the Mechanical Precision Laboratory, Malaysia-Japan International Institute of Technology. The schematic illustration of the experimental setup is as shown in Figure 1. The emission sampling port, thermocouple probes position, and Kyowa EDX data logger are also shown in the figure. The industrial burner is installed to a furnace which has its first 5 temperature measurement ports, each inserted with a thermocouple probe as that is maximum flame length reported to have been observed in this study. The distance between each temperature measurement ports is approximately 140 mm.

The industrial burner that is used in this study was a dual stage heavy oil pressure jet FBR burner FNDP 45/2, as shown in Figure 2. All the tested fuels were preheated in the burner system to 50 C automatically, and the range of fuel flow rate of the burner is 20-45 kg/h. The burner fan damper is equipped with a numbered angle-controller (fan damper number: 0 - 8) that can be adjusted to increase the opening angle of the damper, hence the amount of the air admitted to the furnace. In this study, only 3 types of fan damper numbers were used; 2, 3, and 4, which has an inlet air mass flow rate of 0.11 kg/s, 0.39kg/s and 0.63 kg/s, respectively. Fan damper numbers lower or higher than these were not used in this study because they caused the fire to extinguish.

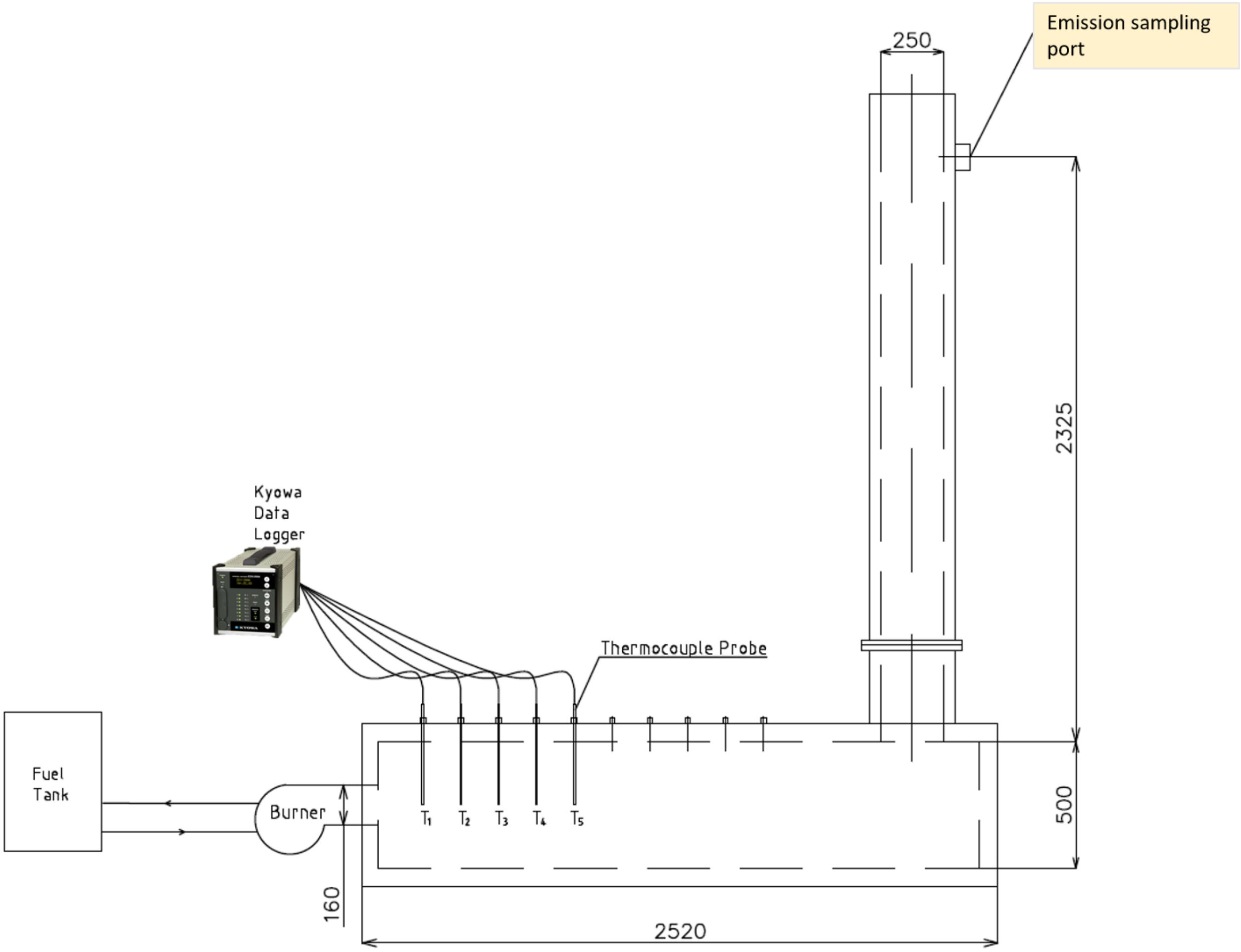


Fig. 1. A schematic illustration of the experimental setup

Fig. 2. The burner used in the present study (FNDP 45/2)

2.2 Fuel Preparation

The study was conducted using Malaysian Diesel Fuel grade 2 (D2). The percentage of fuel, water and surfactant used in each W/D emulsion fuel was measured by volume. The surfactant added into the W/D emulsion fuel was sorbitan monooleate Span 80 (Polyoxyethyleneonylphenyl) with Hydrophilic-Lipophilic Balance (HLB) of 4.3, while the water added was tap water. Three different W/D emulsion fuel were prepared by mixing D2 with 1% of Span 80 and different water percentages (5%, 10% and 15%), and were labelled E5, E10 and E15, respectively. Each W/D emulsion fuels was mixed using a conventional agitator mixer at a speed of 2500 rpm for 5 minutes. The test fuel samples were shown in Figure 3, and the physical properties of D2 is given in Table 1.

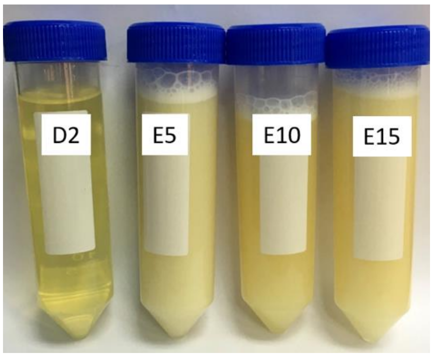


Fig. 3. The test fuel samples used in the experiment

Table 1
Specifications of D2 [19]

Properties	Unit	D2
Calorific Value	MJ/kg	45.280
Cloud Point	°C	18
Density @ 15°C	Kg/L	0.8538
Total Sulphur	Mass %	0.28
Viscosity @ 40°C	cSt	4.642
Distillation Temperature, 90% recovery	°C	367.9
Flash Point	°C	93.0
Pour Point	°C	12
Cetane Number	-	54.6
Carbon Number	wt %	84.1
Carbon	wt %	12.8
Hydrogen	wt %	12.8
Sulphur	wt %	0.2
Nitrogen	wt %	<0.1
Oxygen	wt %	3.9

2.3 Viscosity and Density Test

The density of each test fuels was measured using a pycnometer and a weighing scale to the nearest 0.001 g, and then the viscosity was measured using an Expert Series Fungi Lab-Viscometer, with measurement sensitivity of ± 0.1 cSt.

2.4 Fuel Consumption Measurement

In this study, the weight of the fuel tank before, w_i and after, w_f each test was measured using a weighing scale. The burner run time, *t* was also recorded using a stopwatch. The fuel consumption of D2 was calculated using Eq. (1) as shown below

$$Fuel\ Consumption = \frac{w_i(kg) - w_f(kg)}{t\ (h)} \quad \text{(kg/h)} \tag{1}$$

The fuel consumption of E5 and E10 was calculated using Eq. (2) due to the added surfactant.

$$Fuel\ Consumption = \frac{(w_i(kg) - w_f(kg))(100\% - water\ percentage(\%) - surfactant\ percentage(\%))}{t\ (h)}\ (kg/h) \quad (2)$$

2.5 Flame Temperature Measurement

The flame temperature was measured using 5 K-type thermocouple probes, each inserted in the temperature measurement ports (refer Figure 1). All 5 thermocouple probes were connected to a Kyowa EDX-200A data logger which can record multiples flame temperature reading simultaneously. Each temperature sampling ports were labelled as T1, T2, T3, T4 and T5, where T1 is the nearest to the burner, and T5 is the farthest.

2.6 Emissions Measurement

The exhaust emissions that were measured in this study are NO_x and CO. The emissions were measured using a TESTO 350 emission analyser. The measurement was measured at the emission sampling port located on the chimney (refer Figure 1). The specifications of TESTO 350 emission analyser are shown in Table 2 below.

Table 2
The specifications of the TESTO 350 portable emission analyser

Parameter	Range	Resolution	Accuracy
O2	0 – 25 %	0.01 %	±0.2% vol.
CO (H_2 compensated)	0 – 10000 ppm	1 ppm	±5 ppm (0 – 199 ppm) ±5% of mv (200 - 200 ppm) ±10% of mv (2001 – 10000 ppm)
CO_{low} (H_2 compensated)	0 – 500 ppm	0.1 ppm	±2 ppm (0 – 39.9 ppm) ±5% of mv (40 – 500 ppm)
NO	0 – 4000 ppm	1 ppm	±5 ppm (0 – 99 ppm) ±5% of mv (100 – 1999.9 ppm) ±10 of mv (2000 to 4000 ppm)
NO_{low}	300 – 1500 ppm	0.1 ppm	±2 ppm (0 – 39.9 ppm) ±5% of mv (40 – 300 ppm)
NO_2	0 – 500 ppm	0.1 ppm	±5 ppm (0 – 99.9 ppm) ±5% of mv (100 – 500 ppm)
CxHy	-	10 ppm	±2% of mv

3. Results and Discussion
3.1 Fuel Density and Viscosity

The density of tested fuels is shown in Figure 4 below. The chart shows that the density of the tested fuels increased with the increase in water amount. The density of tested fuels increased with the addition of water due to the higher density of water than that of D2.

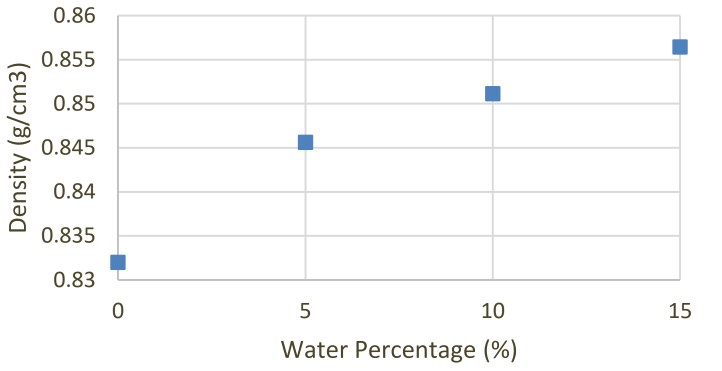


Fig. 4. The value of measured density as a function of the water content in the tested fuel samples

The viscosity of a fuel can influence the combustion characteristics such as increasing the spray angle of the fuel or lengthen the spray distance [20–22]. Figure 5 shows the kinematic viscosity of the fuel samples prepared and tested in the present study. D2 had the lowest viscosity, and the viscosity increased with the increase of water content. Increasing the water content in W/D emulsion fuel increases the number of its dispersed phase. This leads to larger surface area between the dispersed phase and continuous phase, making the fuel more viscous [23].

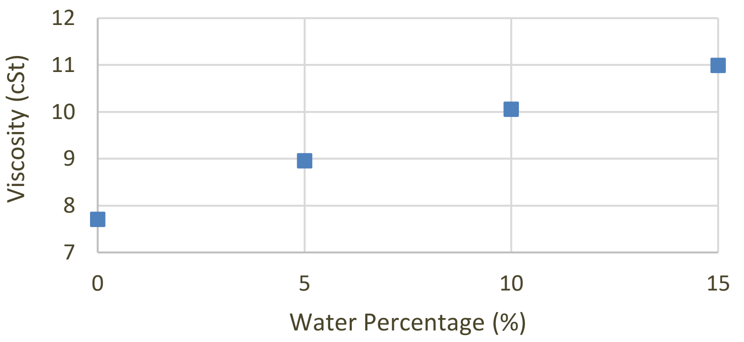


Fig. 5. The value of measured viscosity as a function of the water content in the tested fuel samples

3.2 Fuel Consumption

Figure 6 shows the fuel consumption of all the tested fuels at different fan damper numbers except for E15 at damper 4. The fuel consumption, flame temperature and exhaust emission of E15 at damper 4 could not be included in this study, because the flame extinguished with that setting. This may be caused by the high viscosity of E15 and the limitation of the burner itself as it has a minimum fuel delivery flow rate of 20kg/h. At damper 2 and 3, the highest fuel consumption was that of D2 at 25.84 kg/h and 24.15 kg/h, respectively. At damper 4, the highest fuel consumption was that of E5 at 24.45 kg/h. At fan damper 2 and 3, the fuel consumption decreased with the increase in water content in the fuels. This can be explained by the occurrence of micro-explosion during the combustion of these fuels. When the fuel droplets are released into the combustion chamber, micro-explosion phenomenon further breaks these fuel droplets into smaller droplets which increases the air-to-fuel surface area. Therefore, improves the burning efficiency of the fuel and reduces fuel consumption [24]. However, at damper 4, the increase of water has no impact in the reduction of fuel consumption.

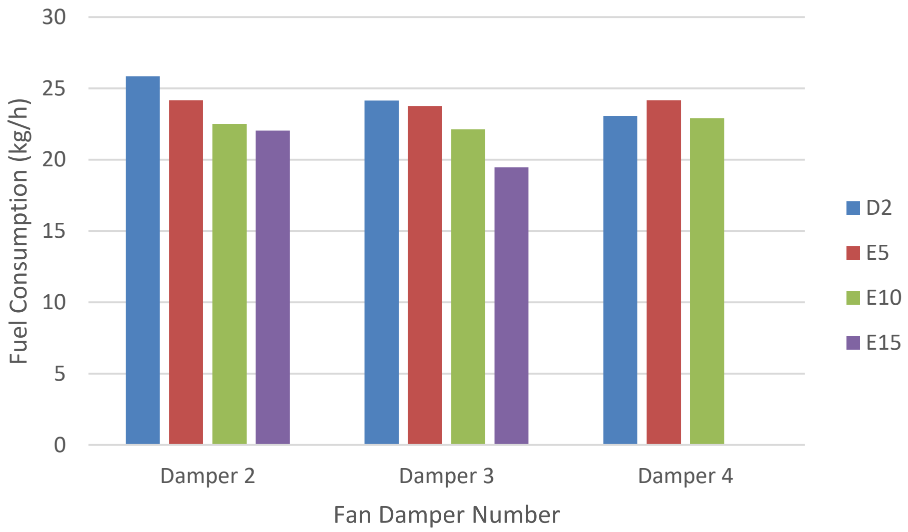
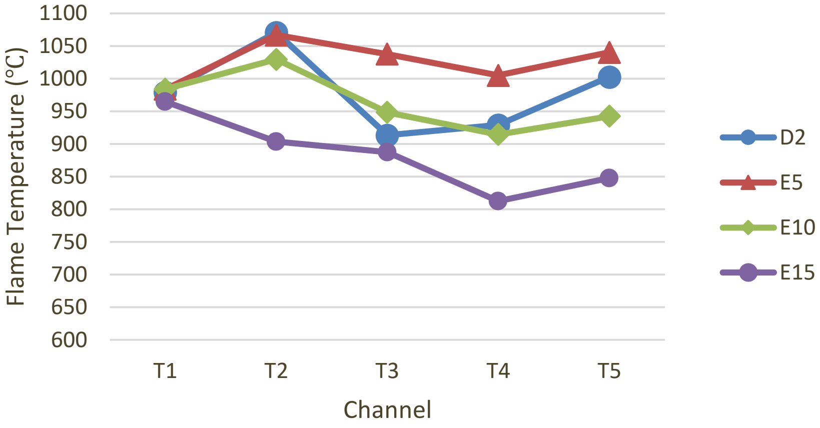


Fig. 6. The fuel consumption of all tested fuels with the variation in fan damper number

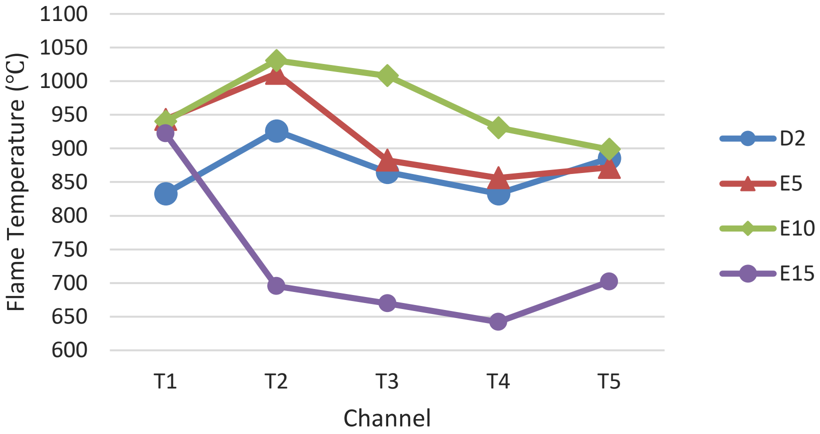
3.3 Flame Temperature

Figure 7(a)-(c) shows the flame temperature of the tested fuels at fan damper setting number 2, 3, and 4, respectively. At damper 2 and 3, the highest flame temperature of the tested fuels was observed at channel 2, whereas the highest flame temperature observed at damper 4 was at channel 1. Each tested fuel also showed different temperature pattern at each damper number setting. For example, E5 had the highest flame temperature at damper 2, but not at damper 3 and 4. It was also observed that damper 2 produced the highest flame temperature compared to damper 3 and 4. From this observation, damper 2 provided sufficient air for the combustion of all tested fuels.

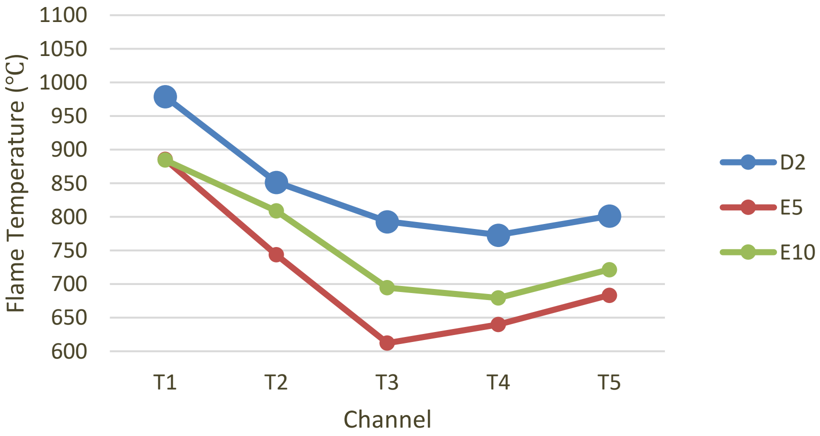
At damper 2 and 3, E5 and E10 had higher flame temperature than D2 and this may be caused by the presence of surfactant in the fuel, which is similar to an investigation conducted by Jahani and Gollahalli [21], where they discovered that the addition of surfactant increased the flame temperature. The presence of water in the fuel also causes micro-explosion which improved the combustion [20]. However, the increase in water content in W/D emulsion fuels also decreased the flame temperature at fan damper 2. The reduction of flame temperature can be explained by the high latent heat of evaporation of the water in W/D emulsion fuel absorbs the heat during the combustion [17,25]. Despite having higher water content, E10 had higher flame temperature than that of E5 and E15 at damper 3, which means that damper 3 setting is suitable for E10. It was also observed that the increase in excess air supply decreased the flame temperature, which is consistent to with the results reported by Ghorbani *et al.,* [26].



(a)



(b)



(c)

Fig. 7. The flame temperature of all the tested fuels at; (a) damper 2, (b) damper 3 and (c) damper 4

3.4 Exhaust Emission

In this study, the measured exhaust emissions were NO_x and CO, at different fan damper numbers. The results will be further discussed in the next section.

3.4.1 NO_x emission

Figure 8 displays the NO_x emission of the tested fuels at each fan damper setting. D2 had the highest NO_x emission at all fan damper setting. At damper 2 and 3, the NO_x emission decreased with the increase of water amount in the tested fuels, whereas at damper 4, the emissions of all tested fuels were relatively low, indicates that the NO_x formed was by fuel NO_x, not prompt NO_x [27]. The NO_x formed in this study is mainly produced by prompt NO_x, because in order for thermal NO_x to form, the flame temperature needs to be above 1300°C, according to the Zeldovich equation [28,29]. It was also observed, that the NO_x emission decreased with the increase in excess air amount, which is similar to the observation reported by Ghorbani *et al.,* [26]. The addition of water helps to suppress the formation of NO_x in the combustion.

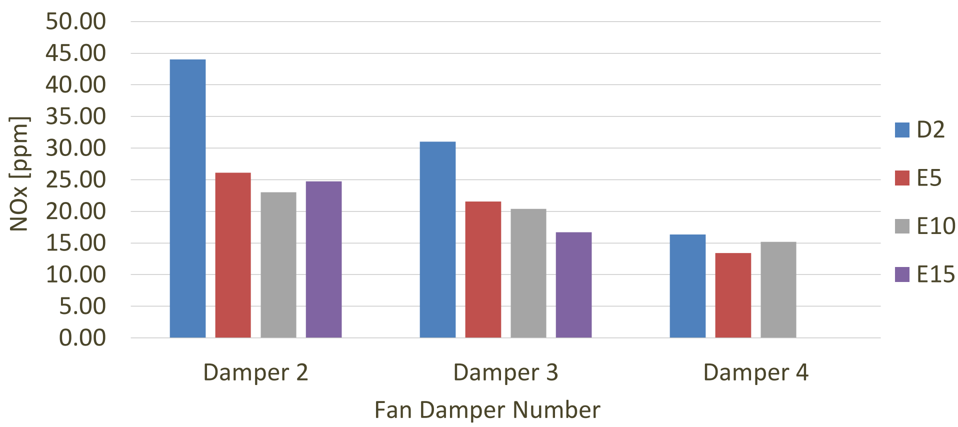


Fig. 8. NO_x emission of all the tested fuels versus the variation in fan damper number

3.4.2 CO emission

CO emission of D2, E5, E10 and E15 are shown in Figure 9. The CO emission of all the tested fuels increased with the increase in the fan damper number. The flame temperature also decreased by increasing the inlet air mass flow rate, which increased the CO emission of all the tested fuels, in a manner similar to the results reported by Bazooyar *et al.,* [30]. The increase in the CO emission of W/D emulsion fuel also increased by increasing the water content in the fuel. The reduction of CO emission by E5 at damper 2, 3, and 4 are 36%, 22%, and 26%. The reduction of CO emission by E10 and E15 were not as much as E5, but both W/D emulsion fuels showed CO emission reduction at every fan damper number. This indicates that micro-explosion that occurred in the combustion of E5, E10 and E15 promoted cleaner combustion, thus reducing CO emission, as reported in several studies [17, 18, 31]. Furthermore, the addition of water in the fuel leads to the increase in the hydroxyl (OH) radicals that aid the oxidation of CO, hence the reduction of CO from W/D emulsion fuels [29].

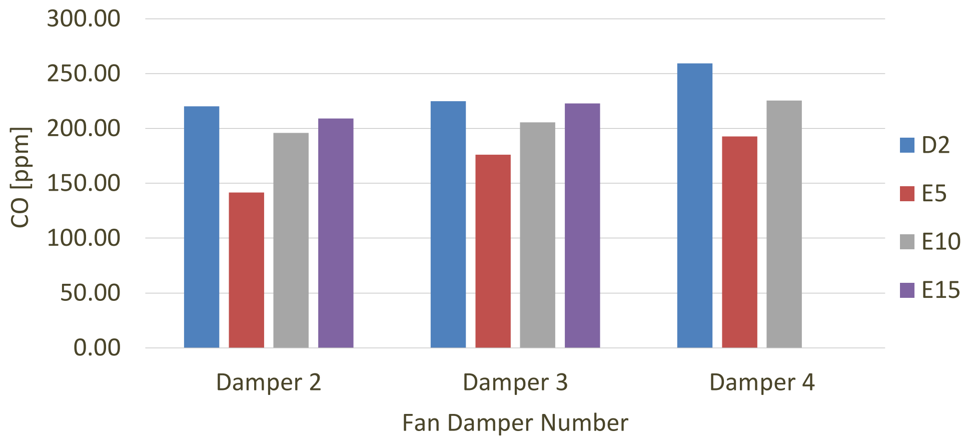


Fig. 9. CO emission of all the tested fuels with the variation in fan damper number

3.4.3 HC emission

The HC emission levels for all the tested fuels are depicted in Figure 10. Similar to CO emission, HC emission increased with the increase in the inlet air mass flow rate. At damper 3, HC emission of D2 was almost twice as that of the emission of D2 at damper 2. The HC emission also increased by increasing the water content in the W/D emulsion fuels. E5 showed the lowest CO emission at all fan damper setting and it is the lowest at fan damper 2 setting. The trend of HC emission of the tested fuels was similar to that of CO emission (refer Figure 8) because the formation of HC is related to the formation of CO, as incomplete combustion produces both emissions as by-products [16,32–34].

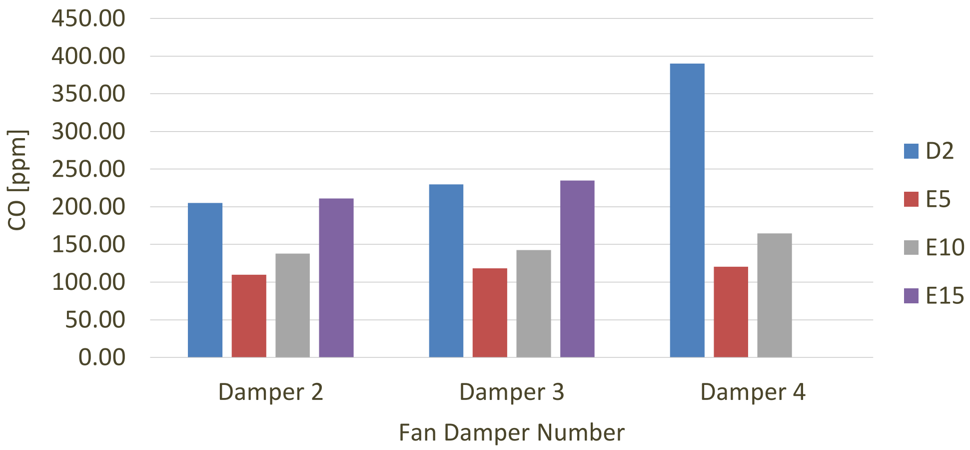


Fig. 10. HC emission of all the tested fuels with the variation in fan damper number

4. Conclusions

Based on the results of this study, the density and viscosity of the tested fuels increased with the increase in water amount in the fuel. The flame temperature of all the tested fuels were the highest at fan damper 2, where E5 shows the best combustion performance based on its flame temperature. The results on fuel consumption for all tested fuels at all fan damper setting did not show a significant change, although the fuel consumption for E5, E10 and E15 were slightly lower than that of D2 at fan damper 3 and 4. Although NO_x emission at damper 2 is higher than that of other dampers, lower CO and HC emission at fan damper 2 suggested that the best fan damper setting for all the tested fuels is damper 2. In conclusion, fan damper 2, with the inlet air flow of 0.11 kg/s is the best fan damper setting for E5, as the amount of air supplied is sufficient to promote cleaner combustion with the aid of water in the fuel.

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