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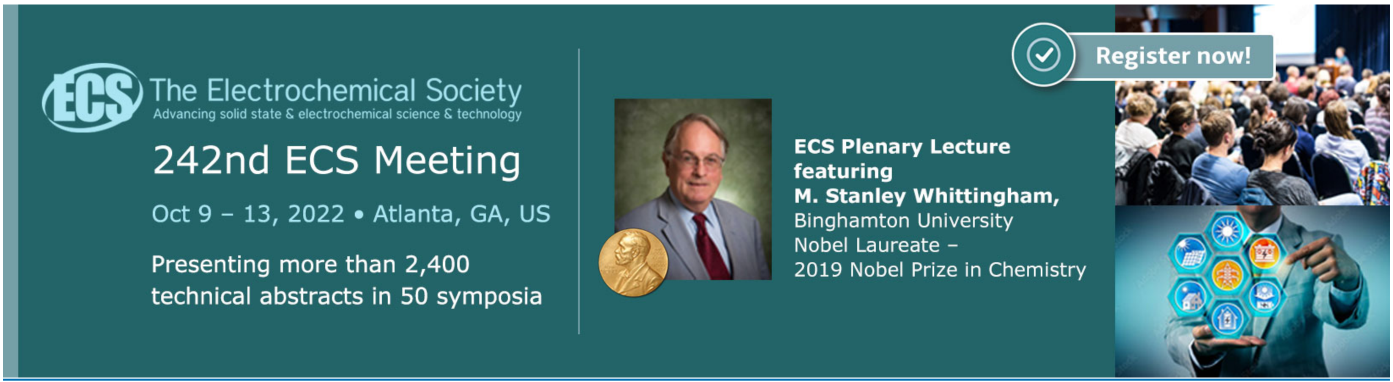

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Diesel engine fuel consumption and emission analysis using steam generated non-surfactant water-in-diesel emulsion fuel

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Abstract. Efforts in making water in diesel emulsion (W/D) with the absence of surfactant have been developed to address the issues of long-term stability and the dependence on surfactants. This paper discusses an alternative formation method of a non-surfactant W/D, e.g. by steam condensation. By injecting steam into a batch of colder diesel fuel, fine water droplets are formed and suspended in the fuel forming an emulsion. The droplets are confirmed to be in the size range of hundreds of nanometers. The emissions of NOx is reduced by a maximum of 71%, whereas the CO and UHC emissions are increased by maximum respectively 180% and a surprising 517%. Not less interesting is the lower BSFC which was measured at a maximum reduction of 18.4%. These results on emission analysis together with the brake specific fuel consumption confirm this method to resemble the combustion behaviour of a conventional emulsion fuel of lower NOx and BSFC, yet higher CO and UHC

1. Introduction

Interest in the research of water-in-diesel emulsion (W/D) is growing since while it is an alternative fuel that can reduce the emission of nitrogen oxides (NOx), black smoke and particulate matter (PM) simultaneously, it also improves the combustion efficiency. Moreover, W/D can be used in a regular diesel engine without major modification[1, 2].

Conventional W/D is defined as an immiscible blend of water droplets (dispersed/internal phase) in diesel (continuous/external phase) [3]. A surfactant in low concentrations is added to prolong emulsions stability and lower the energy requirement [4], which is often supplied by mechanical agitation [5].

In 2015 at the VSE Lab in MJIIT-UTM Malaysia, Muhsin developed a system called the RTES (Real Time non-surfactant Emulsion Fuel Supply System). This system produces non-surfactant W/D by combining an ultrasonic transducer with a high shear mixer and was proven to be able to feed a 5 kW stationary engine [6] and a light-duty lorry [7]. This method of fuel preparation utilises mechanically rotating and electronic components such as additional pumps, high-shear mixer, an ultrasonic transducer, which need extra investment, operating and maintenance costs. To reduce these other costs, finding alternatives on reducing these components makes a good case.

The alternative is found in steam, where water in vapour state will condense in contact with sub-cooled diesel. In this concept, steam would change phase and lose its sensible heat in the sub-cooled diesel [8]. Because of the nucleation phenomena [9] and the turbulent condition, very small water droplets may be produced, dispersed and suspended in the diesel.

Therefore, this articles main objective is to evaluate the feasibility of the concept of making non-surfactant W/D through steam condensation method. The evaluation is performed by characterising the water droplet size of the produced fuel and analysing its emission and the brake- specific fuel consumption (BSFC) on a single cylinder diesel engine.

2. Experimental

2.1. Materials

In this study, the main components are diesel and water. For diesel, Euro 2 standard diesel (D2) with physical characteristics tabulated in Table 1 was used as the continuous emulsion phase. As for water, Malaysian tap water was used with no pre-treatment, and its characteristics are tabulated in Table 2 [10].

2.2. Emulsion preparation

The preparation of W/D was set up with the help of a glass column with multiple nozzles as illustrated in Figure 1.The column is filled with diesel entering the column through nozzle 2. Steam is then supplied from a steam generator through nozzle 5 generating bubbles in the diesel pool. When emulsified fuel overflows nozzle 4, it will exit the flash and go to the fuel injector into the combustion chamber. Some condensate will enter the flash due to the saturation of the steam and will eventually discharge through nozzle
6. Through nozzle 1 some uncondensed steam will exit the column.

2.3. Measurements

After the emulsion is formed, a sample from the sampling point is taken for further analyses, which are water percentage and droplet size distribution.

2.3.1. Water percentages The amount of water forming the emulsion droplets cannot be directly measured since the vapour condensation rate is unknown as some steam leaves the system uncondensed. Instead, to find the water percentages in samples, distillation is performed at a temperature of 140C.

2.3.2. Droplet size and its distribution Water droplet size plays a significant role in altering the combustion behaviour, due to its role as an agent that causes the micro-explosion phenomenon [1]. To determine the droplet size distribution, a laserdiffraction particle-size-analyzer (Shimadzu SALD 2300) was used to analyse the droplet size distribution. The SALD claims to be able to examine across a broad particle concentration range of 0.1 ppm to 20%, and its measurement range covers particle sizes from 17 nm to 2,500 m. The refractive index of water as a dispersant is required for accurate determination of small particle sizes and should be at 1.3325 [11]. However, because such value could not be selected with the SALD, a value of 1.35 with an imaginary index of 0 was used.

2.3.3. Emission analysis The produced emulsion from subsection 2.2 is supplied to a 5.5 kW naturally aspirated indirect injection diesel engine with a configuration as illustrated in Figure 2. The setup followed the SAE Engine Test Code J816b and focused on monitoring the NOx, CO and unburned hydrocarbons (UHC) emission. Exhaust emission is sampled and monitored every 10 seconds for 5 minutes with E-Instruments E4500 portable emission analyser; an average was then considered for the discussion. The engine is coupled to an engine dyno with variable torque to exert variable loads between 0 to 5 kW to measure the emission. The BSFC of D2 and emulsion fuel is measured by using a burette installed after the mixer.

Table 1. Malaysian Euro 2 Diesel (D2) characteristics

Properties	Unit	Value
Calorific Value	MJ/kg	45.28
Cloud Point	C	18
Density @15C	kg/L	0.8538
Total Sulphur	mass %	0.28
Viscosity	cSt	7.6 @20C
5.1 @40C 4.0 @60C		
Distillation Temperature, 90% recovery	C	367.9
Flashpoint	C	93.0
Pour Point	C	12
Cetane Number		54.6
Carbon	wt %	84.1
Hydrogen	wt %	12.8
Sulphur	wt %	0.2
Nitrogen	wt %	<0.1
Oxygen	wt %	3.9
Dielectric constant		2.1

Table 2. Characteristics of Malaysian tap water

Specification	
Density, g/cm, 25 C	1.02412
Specific conductivity, S/cm , 25 C	0.0532
Viscosity, milipoise , 25 C	9.02
Vapor pressure, mm Hg, 20 C	17.4
Isothermal compressibility, vol/atm, 0 C	46.4 E-6
Surface tension, dyne/cm , 0 C	72.74
Specific heat, J/g C , 17.5 C	3.898
Temperature of Maximum density, C	-3.25
Freezing point, C	-1.91

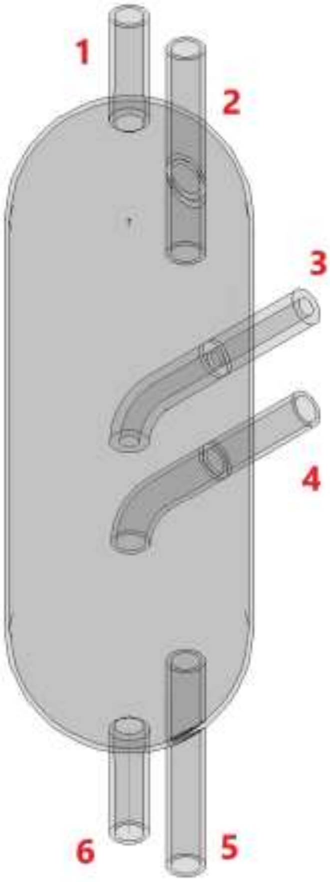

Figure 1. Mixer design

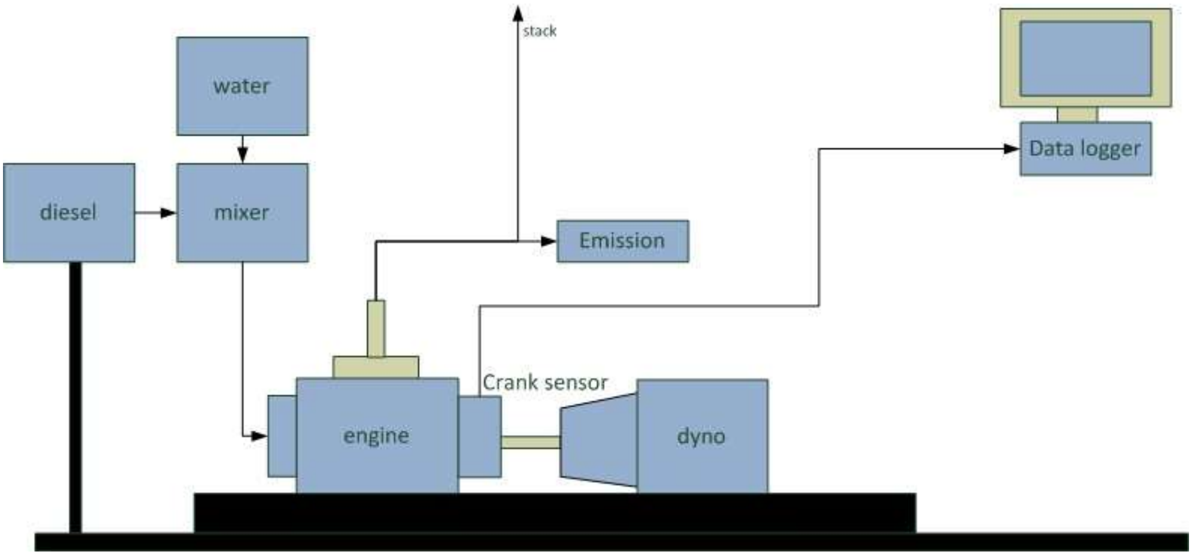

Figure 2. Engine test schematics

3. Results and discussion

The experiment confirms that an emulsion is obtained by the procedure described in 2.2. In Figure 3, it can be observed that the emulsions are yellowish but milky. Water droplets suspended in the diesel cause the milky appearance of the emulsions.

Figure 3. Comparison of D2 and steam-emulsion

When steam enters the mixer, it formed bubbles that rose upward and came into contact with sub-cooled diesel. Wu, et al. stated that the ascending bubbles form nuclei of condensates on its surface [9]. The nuclei will form a layer when the bubble stream is in laminar condition, but turbulence caused by its wake propels and mixes the condensate nuclei into the liquid bulk forming the milky looking substance.

3.1. Droplet size distribution

The presence of the submicron droplets is confirmed by the droplet size distribution measurement using the Shimadzu SALD 2300 as shown in Figure 4. There, the distribution curves show a log-normal distribution with series 1 through 3 belong to a sample measured after 60 minutes after the formation procedure with an interval of 15 minutes between each series.

The graph shows a shift in the average droplet size from around 350 m to 600 m. This shift infers the growth of the droplet size due to the coalescence of the small droplets into bigger ones. This trend can be attributed to the unstable nature of W/D. When the droplets condensed and the emulsion is formed, potential energy to compensate the interfacial tension is stored in the system. Emulsion with small droplets contains bigger potential energy than the one with the larger droplets, so the shift to bigger droplets is inevitable. Eventually, the separation will be complete, and a distinct layer of diesel and water can then be observed, as such layer of their respective indigenous phases is closer to equilibrium.

The fact that the observed sizes after 60 minutes are averaging 350 m also infers that the average droplet size after the formation would be much smaller. However, it could not be confirmed with the sampling method due to the particular preparation time needed before the sample is ready for measurement.

3.2. Water content

During condensation, the bulk temperature of the emulsion rose quickly because of the transfer of latent heat of condensation and conductive heat. With the rising temperature the condensation rate of the steam decreases, so the temperature of the bulk limits the water content of the resulting emulsion.

Abu Zaid [12] observed that the BSFC of W/D decreases by the water content which he evaluated up to 20%. In contrast with that result, the distillation procedure for the steam generated emulsion as described in subsection 2.3.1 yielded smallish and inconsistent average water content ranging from 2.13 to 6.22% as tabulated in Table 3.

3.3. Emission test results

A comparison of the Nitrogen Oxides (NOx), Carbon monoxide (CO) and unburned hydrocarbon (UHC) emission are shown in Figure 5 through Figure 7. It is noticeable that with steam generated emulsion a reduction of NOx at 5kW engine load around 20%

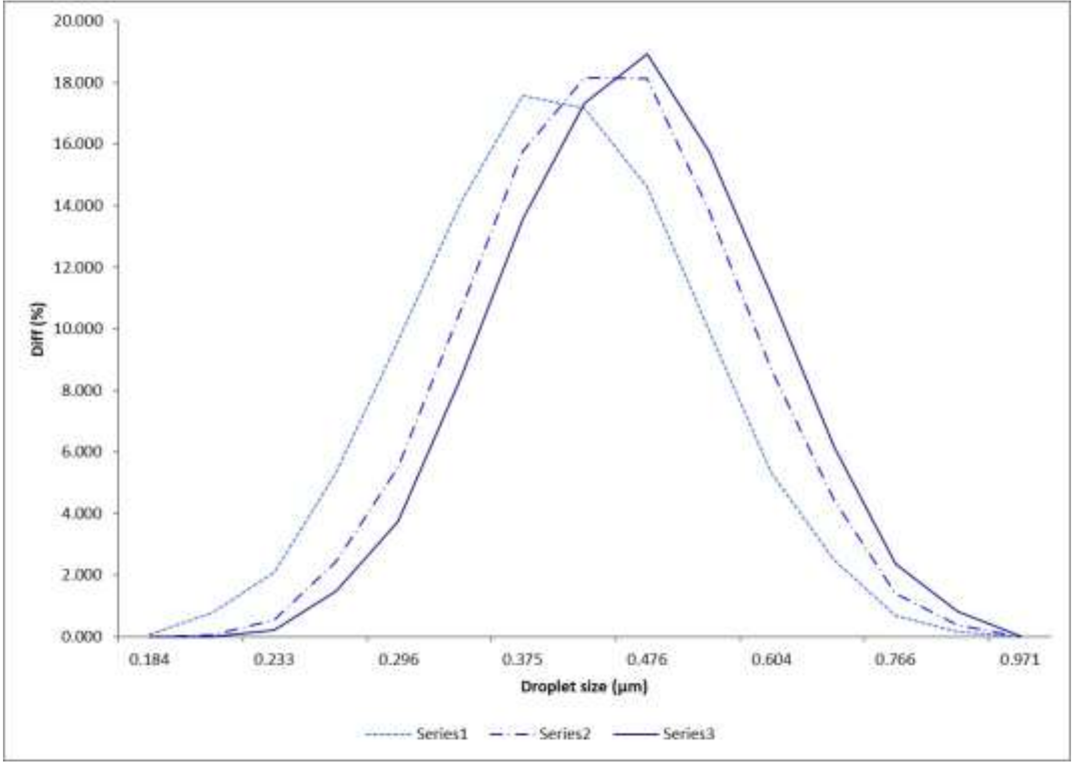

Figure 4. Droplet size distribution and its growth in average size

Table 3. The water content of samples

Load [kW]	Sample water content [mass %]
0	6.22
1	2.13
4	2.14
5	4.38

is achieved compared to D2. However, the CO emission is 50% higher, and the UHC also rises to almost 300%. With emulsion fuel, NOx production is suppressed due to the lower temperature of combustion [13]. CO and UHC increase is also attributed to this decrease in the combustion temperature, causing less complete carbon conversion. These results resemble the problems faced of using W/D as concluded by Murayama et.al.[14] and Subramanian et.al.[15].

3.4. Brake specific fuel consumption

Measurements of the BSFC resulting from both fuels are plotted in Figure 8. Here, the water content is extracted from the calculation. Steam emulsion resulted in overall lower fuel consumption which tally to general findings in W/D research [16, 17, 18]. Murayama et.al. concluded that the BSFC reduction is mainly caused by the microexplosion [14].

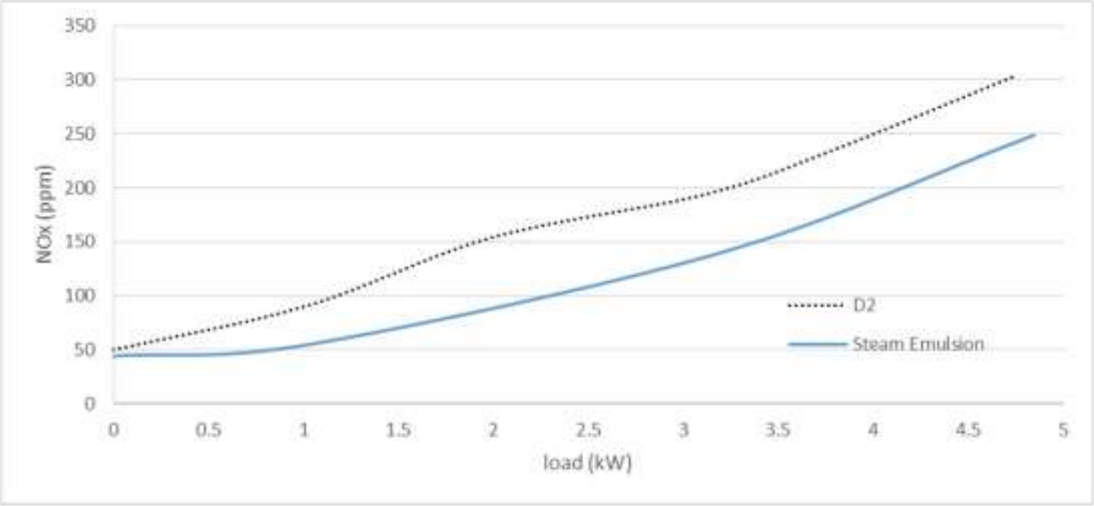

Figure 5. NOx emission

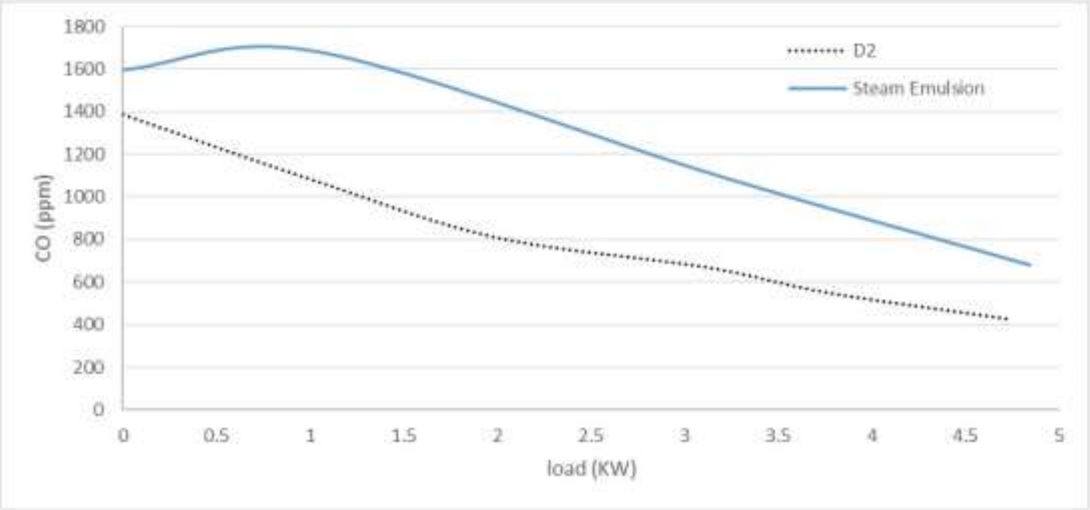

Figure 6. CO emission

The small and inconsistent water content does not hinder the performance of the steam generated emulsion. This boost in BSFC is caused mainly by micro-explosion phenomena. Marrone et al. implied that finer droplet size does not cause better microexplosion [19]. They found in an emulsion fuel with average water droplet size ranging from 2.1 to 4.5 m that the bigger droplets deliver more substantial explosion. The fact that larger droplets perform better micro-explosion confirmed the model by Fu et al. [20] that predicted that the optimum average droplet size is 4.7 m. However, Attia et al.

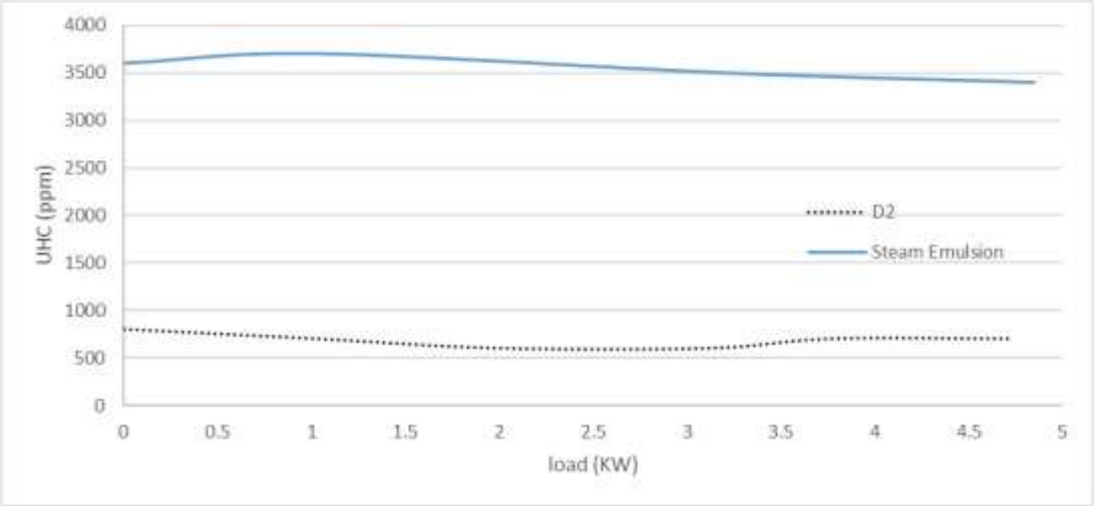

Figure 7. UHC emission

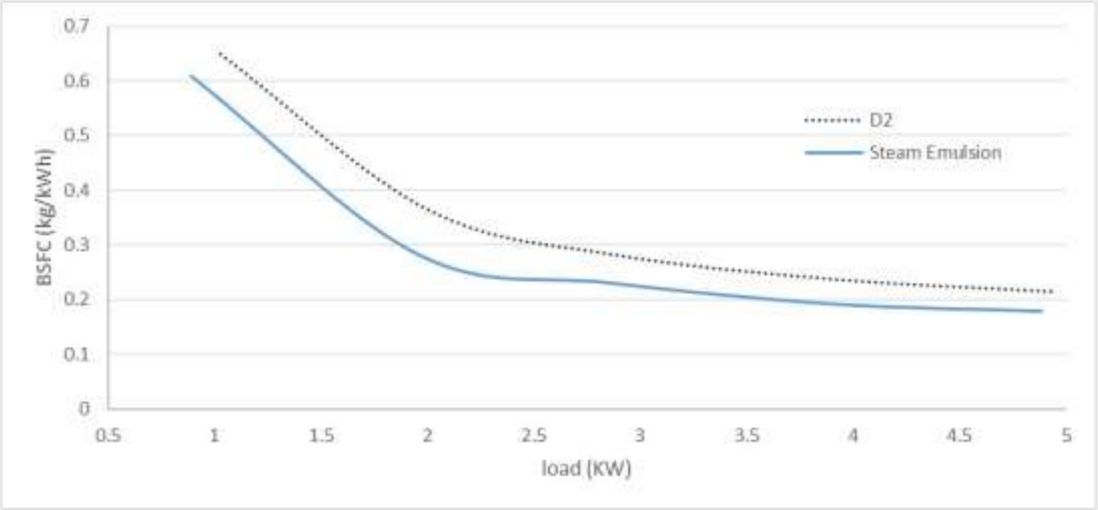

Figure 8. Break specific fuel consumption

reported that smaller droplets cause a notable reduction in the hydrocarbon and smoke level emission in addition to the decrease in engine brake specific fuel consumption. These results were caused by the improvement of the homogeneity of the size distribution and the increase in surface contact between fuel and water droplets which is found in the fine droplets of the steam generated emulsion [21].

4. Conclusions

Reproducible emulsions were formed using the steam condensation method. The mean droplet size observed 60 minutes after preparation process is around 350 m, which is far less than the modelled ideal droplet size of 4.7 m. After the preparation process, the mean droplet size shifts to bigger sizes with the release of the potential formation energy stored in the system. Even though the maximum water content is limited by the bulk emulsion temperature, the droplet population and uniformity of the emulsion compensate the low water content found in steam generated emulsion. The emulsion prepared with steam condensation is proven to be a potential alternative method to yield W/D since it has the characteristics of conventional W/D which are lower NOx (71% max) and BSFC (18.4% max) but higher CO (180%) and UHC (517%) emissions.

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