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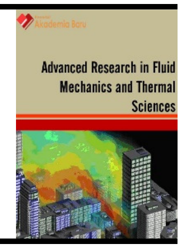

Water Content Determination of Steam Generated Water-In-Diesel Emulsion

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ABSTRACT

Emulsion fuel is one of the prevalent NOx and PM reducing techniques in compression ignition engines. An alternative method to produce emulsion is by mixing steam into diesel involving the condensation of water in the immiscible diesel. The converted steam into water, however, is difficult to determine. Hence, this paper describes a method of estimating the water content of the produced emulsion by using heat balance and Jakob's number equations. Experiments were performed by using a custom designed 250 ml glass column, where final temperatures of the emulsion were recorded, and distillation of the sample was performed to analyze the water content. The results were compared with the equations where Jakob's number model delivers a closer estimate of the experimental values (maximum difference 5.90%) than the heat balance equation (maximum difference 7.93%).

Keywords:
Emulsion fuel, condensation of immiscible liquids, Jakob's number

1. Introduction

The introduction of water into the combustion chamber dated back from before the World War II based on the reports of better thrust and cooler engine on the use of water-alcohol additives in airplanes. In the modern world where emission control becomes a more stringent norm, this method is also proven to reduce the key diesel engine emissions of nitrogen oxides (NOx) and particulate matter (PM) [1]. Methods of water introduction include direct water/steam injection into the combustion chamber, intake manifold fumigation, and emulsion fuel.

Emulsified diesel fuel (W/D) consists of diesel, water, and surfactants mixed in a separate process. The surfactants would keep the emulsion stable for an extended period, in some cases up to several months. The main feature of this emulsion fuel is the so-called micro explosion phenomena, where during the injection the droplets contained in the fuel

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undergoes a sudden superheated phase change causing a burst of secondary fuel atomization illustrated in **Fig. *1*** [2,3].

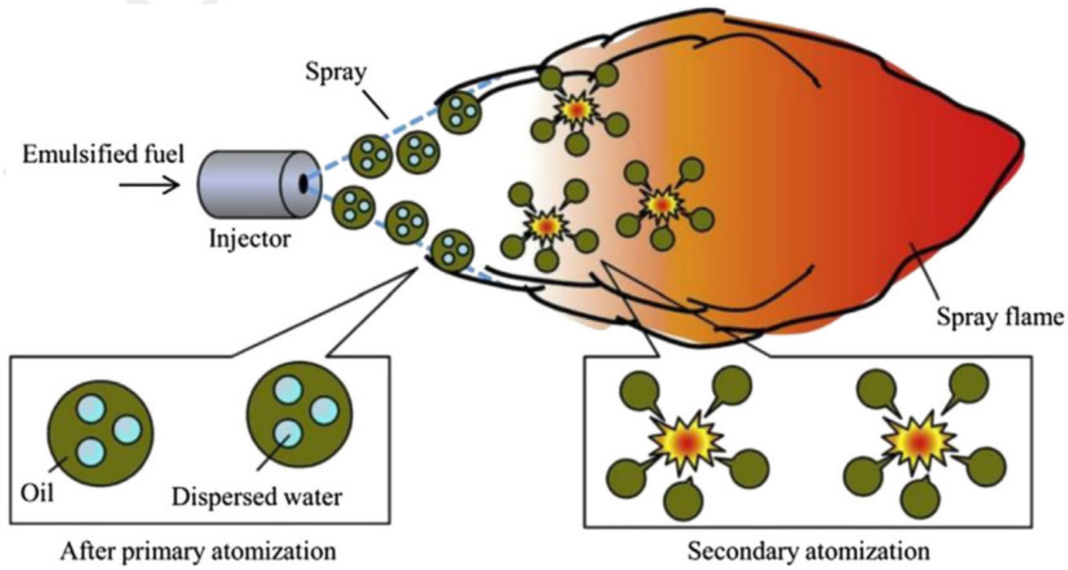

Fig. 1. Microexplosion schematics [4]

Advantages of W/D include similar NOx and PM reduction as direct-water-injection without the needs to modify the engine [5]. Furthermore, no abnormal wear was observed after 200 hours continuous run as opposed to the water injection/fumigation technique [6].

The foremost disadvantage of W/D is the cost of surfactants and its mixing processes. Also, even with the help of surfactants, the water ultimately separates from the emulsion. These drawbacks cause interests to grow in the research of surfactant-less W/D (NW/D). In this concept, diesel and water are stored in separate tanks and mixed in real-time by a high-shear-mixer or an ultrasonic transducer, forming an emulsion just before feeding the engine. The absence of surfactant causes the emulsion to deteriorate rapidly [7], so it needs to be directly supplied to the engine [8].

An alternative concept of emulsion formation was tried by introducing steam directly into a column filled with diesel to create an emulsion [9]. This involves a direct contact condensation [10] of immiscible liquids. The condensation causes the nucleation phenomena [11], where small water nuclei were generated at the steam-diesel interface. The rising steam bubbles create a turbulent mixing and blend the immiscible nuclei to form an emulsion while they partially condense [12]. The product of the nucleation and turbulent mixing was denoted as steam-generated water-in-diesel emulsion fuel (S/D).

The water percentage of an emulsion determines the emission reduction. Most researchers agree that NOx and PM are substantially reduced although the intensity varies between the studies. CO and UHC emission, however, increase in most studies.

With S/D the water percentage is less straightforward to identify because the amount of steam converted to water can be difficult to identify. When steam contacts with colder diesel, it will convert into water. Due to the high latent heat of condensation, the bulk diesel's temperature will rise quickly depending on how much water is condensed. The more steam is converted into water, the hotter the bulk liquid becomes. So, to identify the water content, the temperature of the bulk liquid is an important indicator.

2. Methodology

To create the needed samples, diesel and steam were mixed in a 250-ml custom-made glass column. Diesel entered from a top nozzle while steam entered from a nozzle in the bottom. Eventual water deposit is withdrawn through the blowdown nozzle, while the sample is taken from a side nozzle for about 5 ml per sample.

Euro 2 standard diesel (D2) is selected as base fuel to show whether steam emulsification can be an alternative to improve diesel engines emissions and performance aside from more expensive new engine technology.

Tap water was used in this experiment. It was heated in a steam generator and supplied to the column.

In a previous study [9], engine tests were performed to study the fuel consumption of a 5 kW stationary diesel engine. The results were that the fuel consumption of the engine running on S/D were overall lower than when it ran on neat D2 as shown in **Fig. *2***. On S/D at 5 kW the D2 consumption was around 0.44 ml/s.

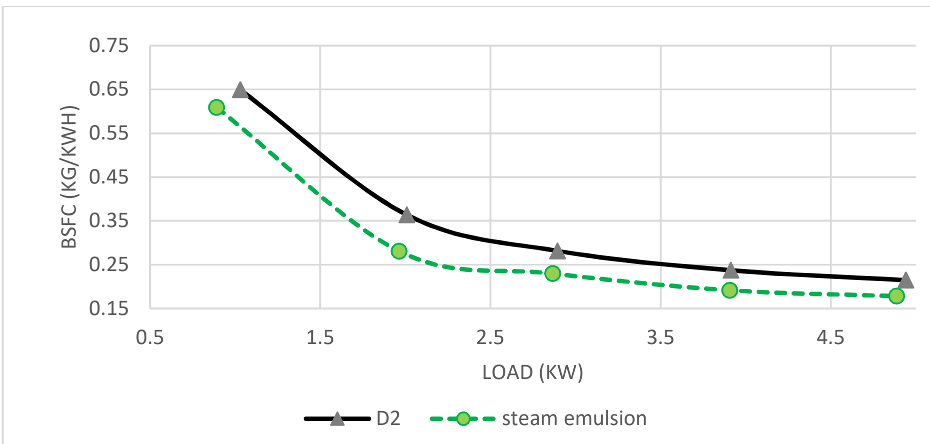

Fig. 2. BSFC of S/D compared to D2 [9]

To simulate the condition on a running engine, the valve V1 was set to supply 0.44 ml/s of D2 which is done by calibrating it against a burette. The column was first filled up to the sampling point, and then diesel together with steam was supplied into the column. A 5 ml emulsion sample was then withdrawn for water content analyses by distillation following the ASTM D95 standards. The samples were heated to 130°C which will evaporate the water as steam bubbles, but low enough to keep the diesel under its boiling point. The distillation process was performed until the emulsion cleared up and no visible steam bubbles were present anymore. The samples were weighed before (m_{d1}) and after the distillation process (m_{d2}) to measure the water mass loss, which converts to the water content f_{mw} as

$$f_{mw} = \frac{m_{d1} - m_{d2}}{m_{d1}} \quad (1)$$

Sensible heat and latent heat of condensation will be released by steam when it contacts with colder diesel. The sensible heat transferred in such a process consists of two parts; the heat of water vapor and condensate before it reaches the equilibrium temperature. Firstly, steam will transfer the heat to the sink until it reaches the dew point, Δh_1. When the steam enters the dew point, it changes phase into liquid water and gradually release the latent heat, Δh_2. As steam changes into water and the sink temperature is still lower, then some more sensible heat will transfer to the sink, Δh_3 until the bulk liquid reaches the target temperature T_1.

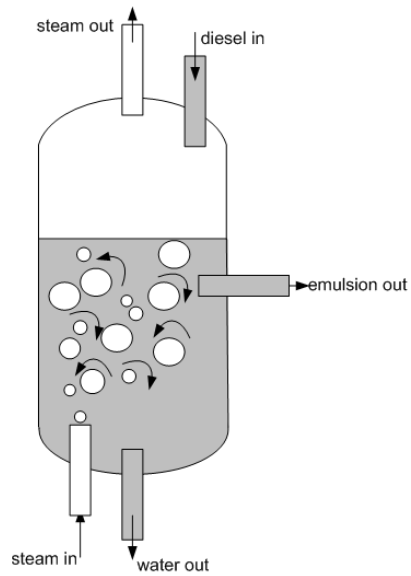

Fig. 3. Experiment setup

The process can be described with the first law of thermodynamics. The initial temperature difference between steam and diesel forms the main driving force for the heat transfer. Steam releases heat Q_{rel}, and changes its phase, while diesel will absorb the heat Q_{abs} until both media reach the equilibrium temperature T_1. The following equation describes the heat balance for the condensed steam m_w in the bulk diesel m_d

$$Q_{rel} = \Delta h_1 + \Delta h_2 + \Delta h_3 = m_w c_{ps}(T_{0s} - T_{dew}) + m_w h_{cond} + m_w c_{pw}(T_{dew} - T_1) \quad (2)$$

$$Q_{abs} = m_d c_{pd}(T_1 - T_{0d}) \quad (3)$$

where T_{0d} is the initial temperature of the diesel, the initial temperature of the steam is T_{0s}, and the final temperature of the emulsion is T_1. As the steam temperature T_{0s} in this setup is near the saturation line T_{dew}, the sensible heat released by the water vapor Δh_1 can be neglected. The water content f_{mw} can then be solved from Equation (1) and (2) yielding

$$f_{mw} = \frac{c_{pd}(T_1 - T_{0d})}{h_w + c_{pw}(T_{ow} - T_1)} \quad (4)$$

Another method used to estimate the water content is by using Jakob's number. This dimensionless number is used to explain the phenomena of heat transfer with a phase change in immiscible liquids. The numbers are calculated using Equation (4) for diesel Ja_d and Equation (5) for steam Ja_s [10].

$$Ja_d = \frac{c_{pd}|T_1 - T_{0d}|}{h_{cond}} \quad (5)$$

$$Ja_s = \frac{c_{ps}|T_{0s} - T_1|}{h_{cond}} \quad (6)$$

The maximum water content in the emulsion can be predicted by the derivation of energy balance using both Jakob's numbers

$$f_{mw} \leq \frac{Ja_d}{1 + Ja_s} \quad (7)$$

From the equations (2) up to (7), it is obvious that the equilibrium temperature T_1 is an important indicator that defines the water content. To validate it, steam was supplied with three different flow settings and kept until the thermocouple was stable.

3. Results

The resulting emulsion is pictured in **Fig. *4***, where it can be compared to neat D2. It can be observed that the emulsion is opaque and light-milky, whereas D2 is translucent and yellow. The milky appearance of the emulsion is caused by suspended submicron water droplets with a lognormal droplet size distribution. The average water droplet size was measured at around 400 nm [9].

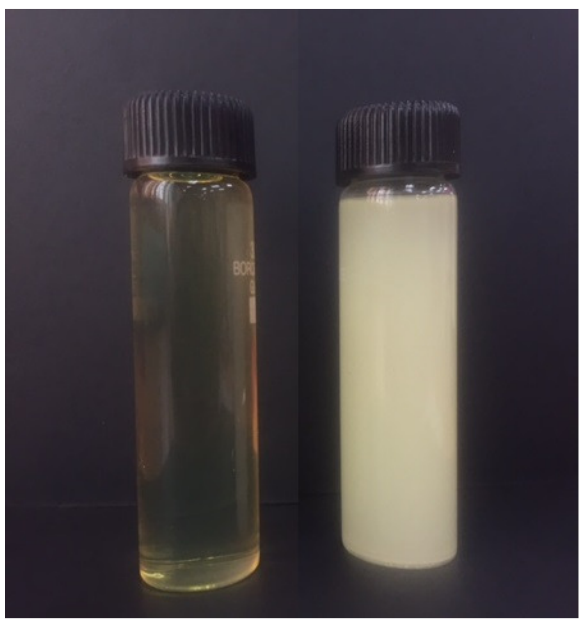

Fig. 4. D2 and S/D sample [9]

The needed heat transfer constants for the equation which involved the phases are tabulated in **Table *1***. It should be noticed that most heat will transfer during the phase change from steam to liquid water, because of the massive h_{cond} value that will single-handedly determine the temperature increase in the final product. The amount of steam converted to water relies thus on how much heat the emulsion can take since even only small amount of condensation will increase the temperature considerably. Initially from its initial temperature, which is around the room temperature of 28°C the bulk temperature will increase quickly but as the temperatures get higher, it will cease to increase due to smaller driving force to cool the steam down.

Table 1
Heat Transfer Constants

Heat of condensation (1 atm, 100°C)	h_{cond}	2257.61 kJ/kg
Heat capacity of diesel	c_{pd}	2.05 kJ/kg°C
Heat capacity of steam	c_{ps}	1.99 kJ/kg°C
Heat capacity of water	c_{pw}	4.179 kJ/kg°C

With three available heat settings in the steam generator a temperature of 50, 70 and 90°C were obtained for the emulsion. Samples were taken, and distillation at 130°C was performed.

Results of the distillation of the samples and heat balance/Jakob's calculation are tabulated in **Table *2***. It can be observed that Jakob's model delivers values which are closer to the experiment results. The equation was calculated with an initial diesel temperature of 28°C and substituting the values in **Table *1***. A graph was then plotted using equation (3) and (6) as illustrated in **Fig. *5***. The trend line for the experiment data is linear with an R^2 of 0.99 which means the linear regression fit the data very good.

Table 2
Distillation results compared to calculation results

	Water content (mass %)		
Emulsion temperature	Experiment	Heat balance	Jakob's
50	2.14	1.82	2.09
51	2.13	1.91	2.18
65	3.75	3.16	3.47
72	4.12	3.80	4.10
72	4.38	3.80	4.10
92	6.22	5.73	5.85

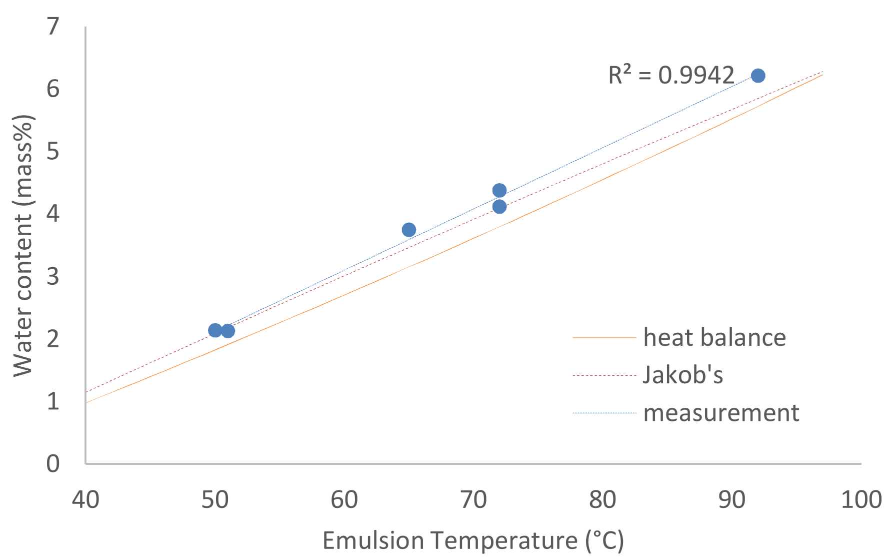

Fig. 5. Comparison of water content against temperature obtained from energy balance calculations

The difference between the heat balance calculation and the experiment values at 92°C was at the maximum 7.93%, whereas Jakob's model differed at maximum 5.90%.

Equation (3) and (6) overall delivered lower water contents than the experiments. This might due to the suspended water in the turbulent emulsion. When a sample is withdrawn the mixing effect preventing droplets from sinking to the bottom of the glass mixer, which causes an increase in the measured water content in the sample.

4. Conclusion

Determining the water content in steam generated emulsion fuel is not as straightforward as a conventional emulsion. Temperature plays a strong indicator to estimate the water content as is proven from the diagram. From this study, it can be concluded that the actual water content can be better predicted with Jakob's number with an error of less than 6%.

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