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Effects of Surfactant Characteristics on Fuel Properties of Emulsions of Alternative Engine Fuel through the Phase Inversion Method

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Abstract: Emulsions that mix two or more immiscible phases are broadly applied in pharmaceuticals, chemistry, and industries. The phase inversion temperature (PIT) method is an emulsifying approach to preparing an emulsion with low energy consumption and cheap equipment. The effects of surfactant characteristics and processes of cooling or heating on the fuel properties of emulsions composed of silicone oil by the emulsifying method, such as mean droplet sizes of the de-ionized water phase, were considered herein. The application of the silicone oil emulsion as engine fuel was first evaluated. The results show that the emulsions added with the polyol surfactant mixture appeared to have a larger mean water-droplet size, a larger number of dispersed water droplets, a wider range of dispersed-water sizes, and lower kinematic viscosity than those with Brij 30 surfactant. Increasing the surfactant concentration of either Tween 20 mixed with Span 80 or Brij 30 surfactant increased kinematic viscosity and the number of dispersed droplets while decreasing mean droplet sizes. After being subjected to fast heating and then fast cooling, the silicone oil emulsion appeared to form many smaller dispersed droplets than those being proceeded with slow cooling. The emulsion of silicone oil was found to have adequate engine fuel properties.

Keywords: emulsion fuel; surfactant characteristics; mean droplet size; kinematic viscosity; fast cooling process; phase inversion temperature



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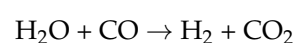
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1. Introduction

Emulsion fuel is successfully used to replace fossil fuel to power internal combustion engines or industrial burners to reduce toxic gas emissions and improve burning efficiency [1,2]. Two-phase water-in-oil (W/O) emulsions or three-phase oil-in-water-in-oil (O/W/O) emulsions are generally used for combustion purposes. The constructive structures of two-phase W/O (water-in-oil) and O/W (oil-in-water) emulsions are illustrated in Figure 1. The secondary atomization of the injected fuel droplets would occur when the emulsion is burned. The water droplets of a dispersed phase are heated, evaporated, and expanded outwards due to the water's relatively lower boiling point in comparison with that of an enveloping oil layer to facilitate the phenomenon of micro-explosion [3]. The total contacting surface and mixing extent between atomized liquid fuel droplets and surrounding air becomes much more increased and intense, leading to a significant enhancement of the reaction rate and, thus, a higher degree of burning efficiency. Both the fuel consumption rate and incomplete combustion products are thereafter greatly reduced. The water–gas shift reaction would also be incurred by the appearance of many small-sized water droplets distributed within an encompassing oil phase [4]. The water–gas shift reaction, which is an exothermic and reversible chemical reaction usually facilitated by an adequate catalyst, is the reaction of hot water steam (H₂O) with carbon monoxide (CO) to form hydrogen gas (H₂) and carbon dioxide (CO₂), which can be expressed as below:



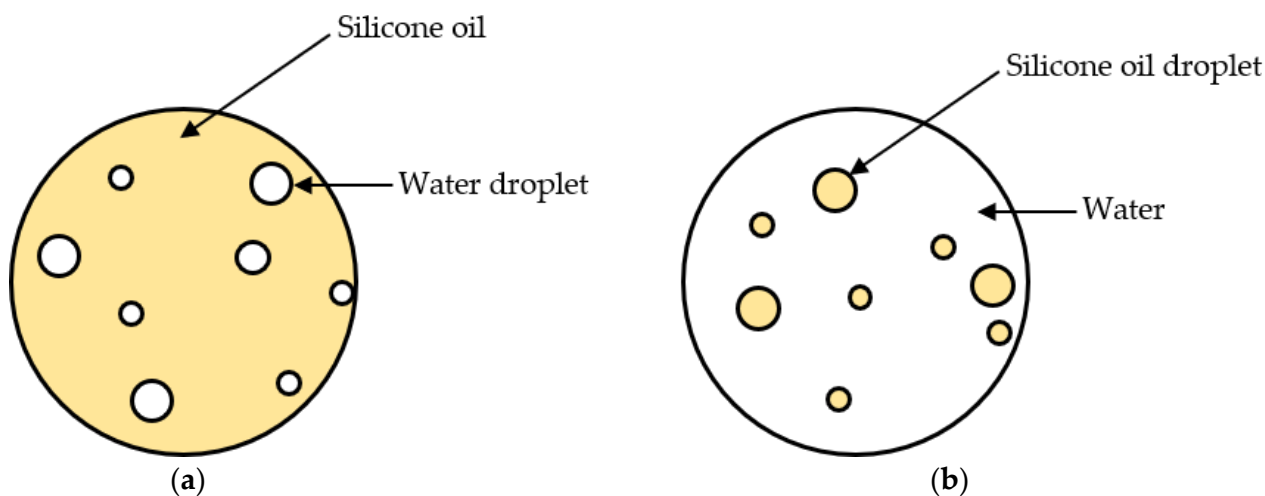


Figure 1. Structure of W/O and O/W emulsions. (a) W/O emulsion; (b) O/W emulsion.

The water–gas shift reaction would enhance the emulsion fuel burning and further convert incomplete products such as CO, HC (unburned hydrocarbons), and black smoke to CO₂ and H₂O [5]. The formation of pollutant emissions would be decreased as well. Emulsification stability, which denotes the time of keeping an unseparated emulsification layer after the emulsion is kept motionless or centrifuged at a high speed, is a dominant property of emulsion fuel. Najjar and Heidari [6] investigated the effects of parameters such as emulsion temperature, stirring speed and time, and surfactant blends of Brij 30, Span 80, Tween 80, and Triton X-100 on the physical properties of the W/O microemulsion of diesel/colza oil and water. The optimum proportions of the components of formulated emulsion appeared to be highly stable and kept no phase separation for at least nine months. The high stability of those emulsions was also ascribed to a very small mean water-droplet size of 4.6 nm. Goodarzi and Zendehboudi [7] also agreed that the droplet size in the dispersed phase of an emulsion is one of the major determining factors for its stability. They considered that available interfacial areas among the emulsion components would alter the physicochemical properties and fluid behaviors of the emulsions to various extents in transport systems. In addition, different fluid properties of emulsions such as kinematic viscosity, salinity, and interfacial tension were found to play dominant roles in emulsion stability. In particular, the presence of highly viscous resins and asphaltenes in marine heavy oil acts like a natural surfactant, which would reduce the interfacial tension between the oil and water phases, resulting in the successful formation of many scattered micro-water particles in the continuous oil phase.

Condensation and dispersion methods are categorized to be low-energy and high-energy emulsification methods, respectively, to prepare emulsions for pharmaceuticals, chemistry, and industrial applications [8]. Ultrasound-assisted, microwave-irradiation, supergravity separation process [9], and mechanical homogenization methods, etc., which require a much larger disruptive force to disintegrate the liquid droplet sizes, are grouped into the latter emulsification methods [10]. In contrast, the former method, particularly the phase inversion temperature approach, uses much simpler preparation instruments and much less emulsification energy [11,12] to prepare emulsions. In addition, this emulsification method compared to its contrast appears to have a significantly higher benefit-to-cost ratio and higher energy efficiency [13]. Moreover, the enforced energy on the emulsion components would not influence the sizes of dispersed droplets of the prepared emulsion [14]. For example, the low-energy emulsification method has been successfully applied to prepare emulsions of nanoscale (2–200 nm) to protect thermal-sensitive flavor components and achieve higher homogeneity among the ingredients of food. Highly stable nano-emulsions can be formed without involving any pressure or shear force to encapsulate food flavors, and this food technology has been developed at a large industrial scale [15]. The low-energy

emulsification method also bears the dominant advantages of low emulsification time and high emulsion formation rate [16].

The temperature at which the corresponding phase change of the emulsion is accompanied by an abrupt electrical conductance drop is defined as the phase inversion temperature (PIT) [17,18]. When the phase inversion temperature approaches, the surfactant's hydrophilic and lipophilic characteristics achieve balance. Hence, the PIT is also denoted as the hydrophilic and lipophilic balance's (HLB) temperature [19]. When the phase inversion temperature (PIT) method is used to prepare the emulsions, the polyoxyethylene (POE) chain-type nonionic surfactant is added [20] to assist the emulsion formation by reduction of interfacial tension among the emulsion components. The hydrophilic-lipophilic properties of those nonionic surfactants are rather sensitive to variations in temperature [21]. The temperature-sensitive polyoxypropylene (POP) chains have been successfully used to prepare nanoemulsions by the PIT method as well. The polyoxypropylene (POP) surfactants were synthesized with hydrophobic long-chain fatty acids and hydrophilic POP diamines through their electrostatic interactions [22]. The hydration of the polyoxyethylene chains in the surfactant would occur [23] due to the temperature shift of the emulsion mixture. In addition, a negative reverse structure appears for such nonionic surfactants at high temperatures and turns to a positive spontaneous curvature when the temperature is reduced [24]. The emulsion of oil-in-water (O/W) is warmed up from ambient temperature to the temperature of phase inversion; the emulsion's electrical conductance drops abruptly [25], and the phase change from oil-in-water (O/W) to water-in-oil (W/O) emulsions occurs simultaneously [26] when PIT is applied [27]. The emulsion's oil, water, and surfactant then reach a co-existent state [28]. Under the equilibrium condition, rather fine dispersed particles in the emulsion are formed with the assistance of mechanical stirring and a cooling process, leading to superior emulsification stability [29]. Many dispersed droplets on a nanometer (nm) scale are generally produced and evenly distributed within the continuous oil phase to enhance the stability of those emulsions prepared by the PIT method [30].

During the emulsification process based on the surfactant compounds used, if a water-in-oil (W/O) emulsion is produced when it reaches a high temperature, the emulsion may be turned into an oil-in-water (O/W) emulsion [31] at ambient temperature. When the emulsion is heated from the surroundings to a sufficiently high temperature, varied emulsion properties and electrical conductance can be observed [32,33]. The PIT method has been found to easily form nano-emulsions with relatively low preparing energy. Ren et al. [34] used the surfactant-containing polyoxypropylene (POP) to prepare n-dodecane-in water nano-emulsions by varying the factors of oil-to-surfactant weight ratio, surfactant concentrations, and NaCl concentration. They concluded that the nano-emulsions have excellent characteristics to be applied in petroleum recovery operations. Wang et al. [35] considered the key emulsification factors such as process conditions and emulsifier combinations for preparing the nano-emulsion of phase change materials (PCM) and water using the PIT method. They found that the nano-emulsion composed of 15% emulsifier and 30% PCM appeared to produce the most stable emulsification layer and superior fluidity. Engels et al. [36] prepared the nano-emulsions of water/C16/18E12, C12/14E4/diaryl ether, water/C16/18E12, and GMS/diaryl ether using the PIT method. The droplet sizes of those emulsions ranged from 50 to 130 nm. Uson et al. [37] used the PIT method to prepare the emulsions of water-in-hydrogenated castor oil and water in the mixture of castor oil and isopropyl myristate. Those emulsions containing dispersed droplet sizes in the range of 60 to 160 nm were found to be steadily stabilized without phase separation for five months.

Silicone oil composed of synthetic organosilicon compounds bears superior chemical and heat-resistance stability, low surface tension, high spraying and penetration capability, low viscosity, etc. It also has high lubricity, great retaining moisture, and excellent film strip formation and, thus, is considered to enhance the lubrication performance of mechanical systems in industrial applications such as thermostat fluids, cosmetics, vitreoretinal surgery, and emulsions [38,39]. The silicone oil emulsions are, thus, considered to own promising

fuel properties such as those stated above. However, the emulsion of silicone oil has previously only been used as heat transfer fluids or long-acting vitreous substitutes, etc. The fuel characteristics of the silicone oil emulsion prepared through the PIT method have never been found in the literature although Lin et al. [40] investigated the effects of various emulsification variables on the emulsion characteristics of silicone oil emulsions. Moreover, the effects of surfactant characteristics and processes of heating/cooling emulsion during phase change on the fuel properties of silicone oil emulsion using the PIT methods [41,42] have not been studied before. Instead, most previous studies only considered the effects of surfactant types on the emulsion stability rather than on the fuel properties [43,44]. Hence, those surfactant characteristics on emulsion properties, such as mean droplet sizes and kinematic viscosity, were systematically analyzed in this experimental study. Various types of nonionic surfactants, which are composed of polyol and polyoxyethylene compounds, were considered to prepare the W/O emulsion of water-in-silicone oil. The fuel properties of the emulsions prepared by various surfactants, preparing time, and cooling/heating processes were analyzed and compared. Figure 2 illustrates the experimental procedures of preparing the emulsions of silicone oil with de-ionized water using the PIT method and the analysis of fuel properties such as mean droplet size and kinematic viscosity under various emulsion preparing conditions. The emulsion fuel could be used as a clean alternative fuel to fossil diesel to mitigate the pollutants emitted from burning liquid fuels and to enhance their burning efficiency.

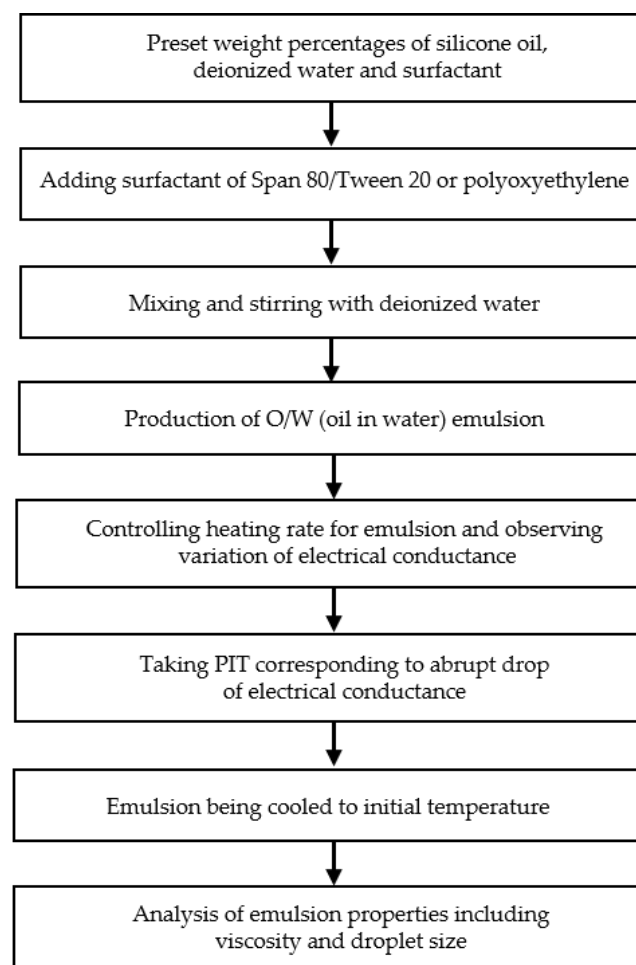


Figure 2. Experimental procedures of preparing and analyzing the emulsion through the PIT method.

2. Experimental Details

The PIT was determined based on the abrupt drop in the emulsion's electrical conductance. Other properties, such as kinematic viscosity accompanied by the variation of the emulsion temperature, were also analyzed. Further, the micro-water droplet sizes of the emulsions, which were heated to their PIT, were observed by an image analyzer and a particle size analyzer. The experimental details applied in this study are explained below.

2.1. Emulsification Materials

Silicone oil ($C_6H_{18}OSi_2$), which is an odorless and colorless liquid, was used to prepare the emulsions of the water-in-oil (W/O) type. The chemical name of silicone oil is hexamethyldisiloxane. The melting point, specific heat, and boiling point of silicone oil are $-59\text{ }^\circ\text{C}$, $1.51\text{ kJ/kg}\cdot\text{K}$, and $101\text{ }^\circ\text{C}$, respectively. It has a relatively lower specific gravity than water, which is 0.963 (at $25\text{ }^\circ\text{C}$). In addition, silicone oil is a highly combustible liquid and can be readily ignited once it meets with high-temperature materials, flame, or strong oxidants. Silicone oil bears excellent electrical insulation, high flash point, small thermal conductivity, and insolubility in water and methanol. It has been used in the chemical industry as an antifoaming agent, a high-temperature dielectric liquid, and a plastic manufacturing lubricant.

Surfactants are composed of molecules belonging to both lipophilic and hydrophilic groups. The HLB value of an emulsifier indicates the relative attraction force for water and oil phases. A surfactant with a higher HLB implies more hydrophilic characteristics. The surfactants Tween 20 and Span 80 are polyol compounds attached with a few hydroxyl compounds. These two surfactants have the characteristics of high boiling points, polar compounds, low volatility, and excellent solubility. The third surfactant, Brij 30, is composed of a polyoxyethylene compound. The surfactants Brij 30, Tween 20, and Span 80 have hydrophilic-lipophilic balance (HLB) values equal to 9.7, 16.7, and 4.3, respectively. Tween 20 and Span 80 of various amounts were blended to have a combined HLB value of 10 based on the weight proportions of the two surfactants and their corresponding HLB values.

2.2. Emulsions Preparation Procedures

The oil-in-water (O/W) emulsions of silicone oil with de-ionized water were formed by the PIT method. The mixture of silicone oil and water at a preset 20/80 weight percentage was added with a surfactant content varying from 1 wt. % to 10 wt. %—it was stirred and heated by a magnetic hot plate stirrer to form oil-in-water (O/W) emulsion. The heating emulsion rate expressed in temperature rise per minute was also controlled by the magnetic hot plate stirrer.

The emulsion was heated from an ambient temperature at $25\text{ }^\circ\text{C}$ to a high phase inversion temperature at which a sudden descent of electrical conductance occurs to prepare the O/W emulsion. Then, the emulsion was followed by a cooling process from the PIT to reach $25\text{ }^\circ\text{C}$. The surface tension among various components in the emulsion tends to decrease abruptly when the emulsion is subjected to a cooling process, triggering phase change. The phase inversion from the emulsions of O/W to W/O structure is finally completed at the end of the cooling process. The cooling rate was controlled from $0\text{ }^\circ\text{C}$ to $3\text{ }^\circ\text{C}$ drop per minute (slow cooling) or from $10\text{ }^\circ\text{C}$ to $15\text{ }^\circ\text{C}$ drop per minute (fast cooling), while the heating rate was from $1\text{ }^\circ\text{C}$ to $2\text{ }^\circ\text{C}$ raise per minute (slow heating) or from $10\text{ }^\circ\text{C}$ to $15\text{ }^\circ\text{C}$ raise per minute (fast heating) until the reach of PIT. A magnetic stirring hot plate was used to heat the emulsions. An ice bath accompanied by the magnetic stirrer was used during the cooling emulsion processes. The solution of sodium chloride (NaCl) of a concentration of 10^{-2} mol/dm^3 was added to the aqueous solution to conveniently observe the variation of electrical conductance before the emulsification process. The heating/cooling of the emulsion processes had four various arrangements, which are a fast/slow heating followed by a fast/slow cooling process. The emulsion fuel properties were thereafter analyzed.

2.3. Measurement of Emulsion Properties

The kinematic viscosity of the emulsions in a unit of cSt or mm^2/s was measured by a capillary viscometer based on the ASTM D445 method. The viscometer was located in a constant-temperature tank at 40 °C. The time t of the emulsion flowing through two indicated points multiplied by viscosity constant k of the viscometer is the measured kinematic viscosity.

Furthermore, the emulsion properties, including mean droplet sizes of the water phase, were measured. The emulsion image and mean droplet size were analyzed by a microscope and an image analyzer during the processes of either heating or cooling the emulsion. An upright fluorescence microscope (BX53 model, Olympus Inc., Tokyo, Japan) along with an image analyzer (TK-C1380 model, JVC Inc., Tokyo, Japan), Image-Pro plus Version 4.1 analysis software (Media Cybernetics Inc., Rockville, MD, USA), and a charge-coupled device (CCD) was applied to analyze the distribution of dispersed water or oil phase and relevant physical structure of the emulsions. A Zetasizer (Nano ZS model, Malvern Inc., Malvern, UK) together with a particle size analyzer (Master 2000 model, Malvern Inc., UK) based on a dynamic light scattering (DLS) approach was adopted to measure the mean size of the dispersed droplets in the emulsion. Each result was obtained from the mean value of repeated experiments carried out 3 to 5 times. The uncertainties of the mean droplet size for the case of emulsions added with surfactant Tween 20 and Span 80 mixture or Brij 30 were 4.32% and 5.16%, and for the kinematic viscosity of the emulsions added with surfactant Tween 20/Span 80 or Brij 30 they were 3.17% and 4.58%, respectively.

3. Results and Discussion

Silicone oil and de-ionized water were treated as oil and water phases in the emulsions. The emulsion fuel characteristics, including kinematic viscosity and mean droplet sizes of the water phase, were measured. An upright fluorescence microscope associated with an image analyzer was applied to analyze the droplet distribution. The experimental results of this study were analyzed and explained in the following sections.

3.1. Effects of Surfactant Type on Mean Droplet Size

The surface tension among the emulsion components tends to decrease with an increase in the emulsion temperature [45]. The emulsion has the lowest surface tension at its corresponding PIT value [46]. Hence, the mean droplet size of the emulsion near the PIT value is smaller than that of the emulsion at a temperature lower than the PIT value. When the emulsion was further cooled down, droplets with even smaller mean sizes were formed. The mean droplet sizes were significantly reduced with the increased concentration of Tween 20 and Span 80, as shown in Figure 3. Lin et al. [40] observed that the increase of the surfactant concentration resulted in the decrease of both the electrical conductance and PIT where an abrupt drop of electrical conductance occurred. The surfactant mixture of Tween 20 and Span 80 caused higher PIT values of the emulsions than that of Brij 30. For example, the PIT had the lowest values, which were 38 °C and 73 °C, respectively, when the surfactant of a 10% concentration of Brij 30 and Tween 20/Span 80 mixture was added to the emulsions.

The results are in accordance with Chuacharoen et al. [47] who prepared curcumin nano-emulsions added with the surfactant mixture of lecithin and Tween 80. They found that the increase of surfactant concentrations from 0.3 wt. % to 9 wt. % significantly reduced the mean droplet size. In addition, the synergistic interface stabilizing effects arising from mixing different surfactants in an emulsion system such as Span 80/Tween 20 surfactant mixture in this study have been recognized by Posocco et al. [48]. The synergistic effects facilitate the formation of stable oil/water emulsions.

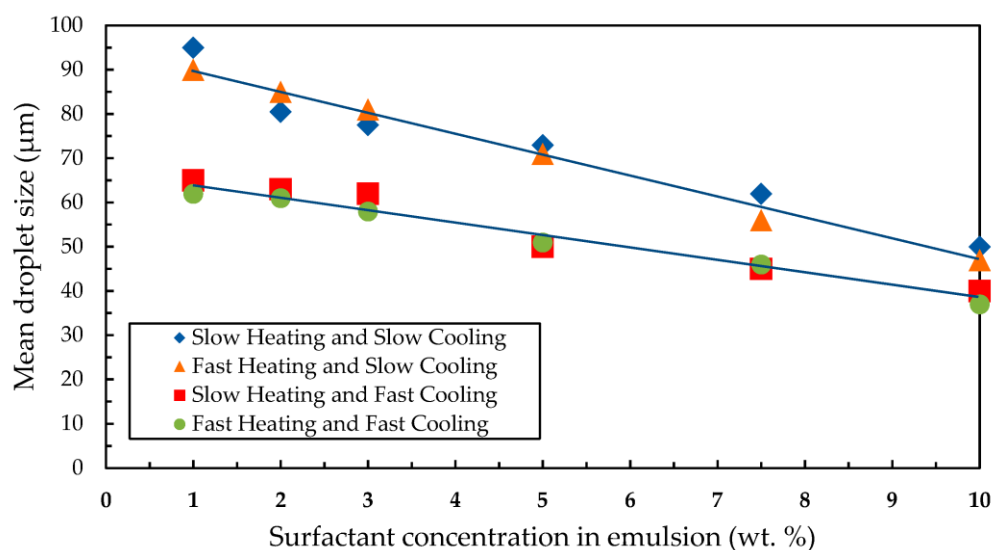


Figure 3. Influences of heating/cooling processes and concentrations of Span 80/Tween 20 on mean droplet size of emulsions.

The smallest droplet size was observed when a concentration of 10 wt. % of the Tween 20 and Span 80 was mixed in the emulsion. This finding might be due to the truth that more surfactant molecules agglomerating along the interphase between oil and water phases decrease the surface tension and reduce the dispersed droplet size. Yekeen et al. [49] investigated the effects of nanoparticle-sized surfactant solutions on the oil-water interfacial tension (IFT) of nanofluids. They used a drop-shape analyzer (DSA 25) and pore-scale visualization to study the interfacial properties of the nanoemulsions and found the available surfactant types significantly influenced interfacial tension and rock-wetting properties. The interfacial tension (IFT) between a nonionic Triton X-100 surfactant and oil phase is also influenced by the salinity, pH, and temperature of the emulsion system. The increase in ionic strength and pH causes a decrease in IFT. In contrast, the IFT increases with the increase of emulsion temperature [50]. Shibata et al. [51] investigated the relationships among the emulsion temperature, hydrophilic interaction, and interfacial tension. Their results demonstrated that the traditional HLB must be associated with strict thermodynamic analysis during the designing process of a surfactant system. The emulsions that were subjected to either slow or fast heating followed by fast cooling decreased the surface tension among the components of the emulsion and reduced droplet sizes compared to the droplet sizes of the emulsions treated with either slow or fast heating and followed with the slow cooling process, as shown in Figure 3. Either slow or fast heating rate had slight effects on the mean droplet size of the emulsions under the assistance of Tween 20 and Span 80. Instead, the fast cooling rate for the emulsion facilitated the significant reduction of mean droplet sizes. When 1 wt. % of Tween 20 and Span 80 mixture was added to the emulsions that were then subjected to a slow heating rate and then a fast cooling rate, the mean droplet size appeared to be 66 µm, which was much lower than that of the emulsion followed with slow cooling rate, which was 95 µm, by 30%. The difference in the mean droplet size between the fast and slow cooling rate decreased slowly with the increase of the surfactant mixture to 23% when 10 wt. % surfactant was added, as shown in Figure 3.

The influences of polyoxyethylene surfactant Brij 30 concentrations and heating/cooling processes on mean droplet sizes are shown in Figure 4. In comparison with the Tween 20 and Span 80 mixture, Brij 30 appeared to be more significant in reducing surface tensions among various components, resulting in reduced emulsion mean droplet sizes, as shown in Figure 4. Eras-Muñoz et al. [52] considered that in comparison with surfactants Span or Tween, Brij 30 surfactant has significant advantages of higher property stability, biodegradability, and toxicity, etc. The emulsions subjected to either slow or fast heating followed

by fast cooling appeared to have more obvious emulsification effects; hence, lower mean droplet sizes than the emulsions beginning with slow/fast heating and then a slow cooling process. The observance for the variation of mean droplet size with heating and cooling processes in Figure 4 is similar to that in Figure 3. The images of micro-water droplets distributed within the emulsion added with a 10 wt. % of Tween 20 and Span 80 mixture or Brij 30 and then a slow/fast cooling process were recorded by an upright fluorescence microscope together with an image analyzer (see Figure 5). The emulsions emulsified with Tween 20 and Span 80 mixture were observed to have a larger number and a wider size range of dispersed droplets compared to the emulsions added with surfactant Brij 30. After being proceeded with fast cooling, the emulsions formed many smaller droplets than those with slow cooling for the emulsions added with surfactant Brij 30 or a mixture of Span 80 and Tween 20, as shown in Figure 5. The mean droplet size for the emulsion added with 1 wt. % Brij 30 surfactant that was subjected to slow heating followed by a fast cooling rate was found to have a significantly reduced mean size of the scattered droplets compared to the emulsion followed by slow cooling by 31%. The increase of surfactant addition to 10 wt. % to the emulsions under a fast cooling rate reduced greatly the mean droplet size to as small as 35 μm and, thus, enhanced significantly the extent of emulsion stability.

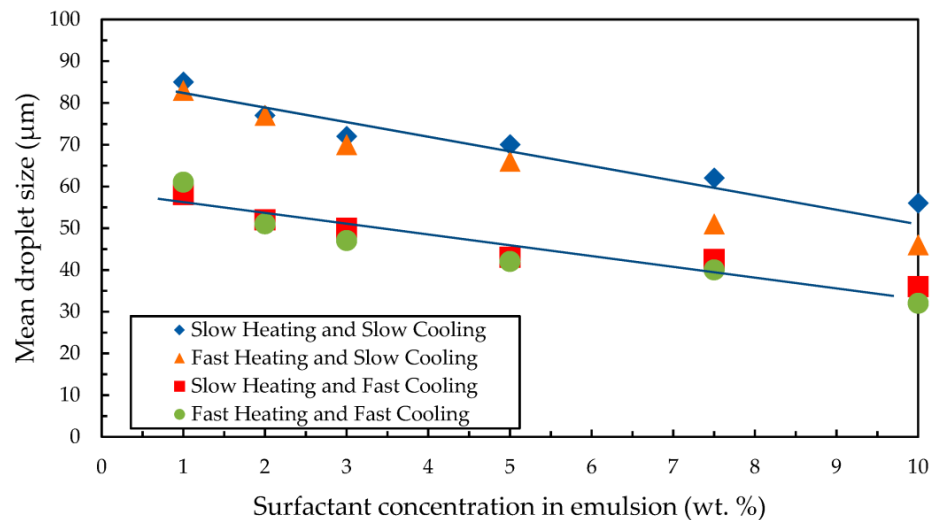


Figure 4. Mean dispersed water droplet size affected by cooling and heating processes and surfactant concentrations of Brij 30 in the emulsions.

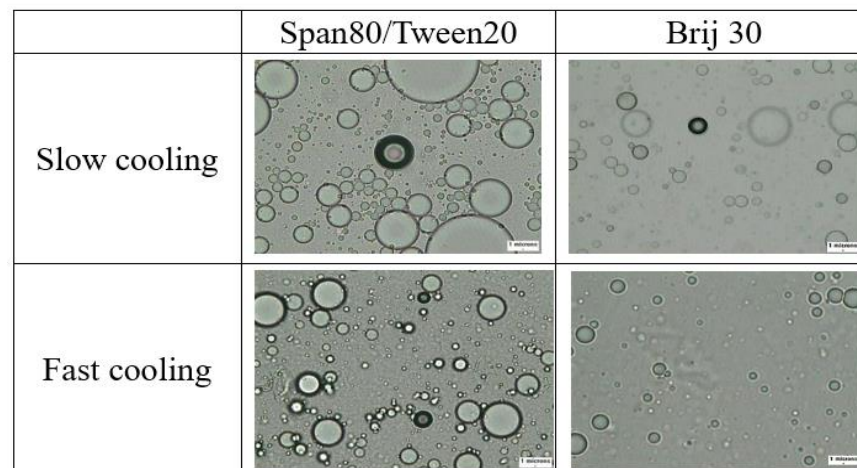


Figure 5. Distribution of dispersed droplets in the emulsions emulsified with 10 wt. % Brij 30 or a mixture of Span 80 and Tween 20 and subjected to various cooling processes.

3.2. Effects of Heating and Cooling Processes on Mean Droplet Size

The PIT of the emulsions was used as the indicator of heating and cooling procedures for the emulsions. For instance, adding 10 wt. % Brij 30 to the emulsion, no significant difference can be observed in the PIT range among the four various combined processes of heating and cooling, as shown in Figure 6. This finding implies that the PIT range was not affected by different processes of heating and cooling. The variation of emulsion temperatures over various processing times of either slow or fast heating followed by different cooling rates was observed in Figure 6. It may take 3 min to reach the PIT under a fast heating rate and 1 min to reach the initial 25 °C by fast cooling. The aqueous solubility is subjected to similar effects within the same temperature range.

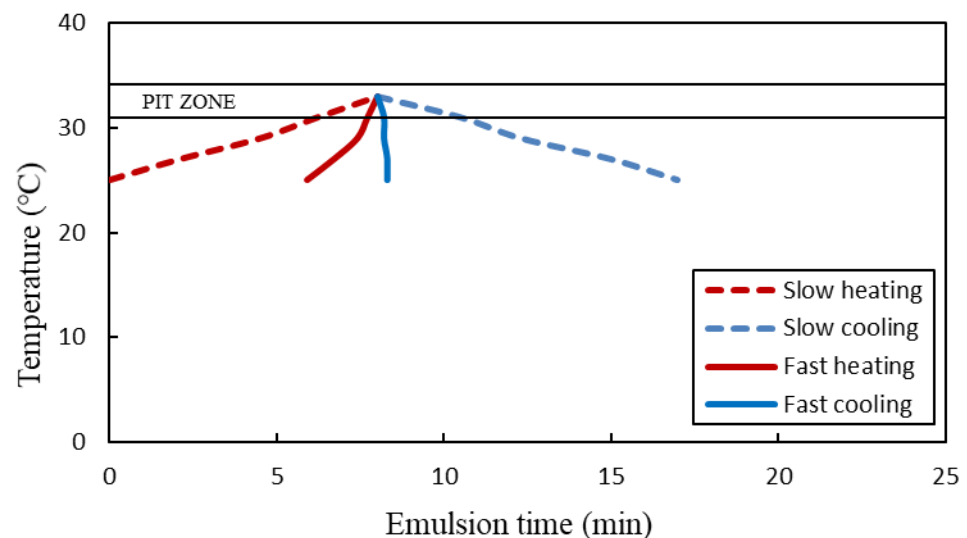


Figure 6. Influence of processing time for the emulsion added with a 10 wt. % Brij 30 subjected to various heating and cooling rates on PIT.

As seen in Figures 3 and 4, the heating rate did not significantly affect the mean dispersed micro-water droplet sizes. However, fast cooling caused the formation of the smallest mean droplet size of the silicone oil emulsion. This result is ascribed to the fact that the lowest surface tension among the emulsion components and the highest solubility capability appeared once the emulsion reached the phase inversion temperature. Feng et al. [53] considered that narrow size distribution, high kinetic stability, and small droplet size were produced when rapid cooling was used to prepare the emulsions close to or at the HLB temperature. Fast coalescence would occur to prevent the nano-emulsion formation under too slow a cooling process. Hence, the smallest droplet size was obtained through fast cooling to the ambient temperature. The phenomenon was also confirmed with the results shown in Figure 4, in which the emulsion, after being added with a 10 wt. % Brij 30 surfactant and subjected to slow cooling, was observed to have larger-sized droplets.

3.3. Effects of Surfactant Type and Concentration on Kinematic Viscosity

The emulsions of silicone oil added with Brij 30 surfactant were shown to have larger kinematic viscosity than those emulsions mixed with Tween 20 and Span 80 in Figure 7. Moreover, the kinematic viscosity of the emulsions added with either Brij 30 or Tween 20 and Span 80 mixture increased with an increase of surfactant concentrations in the emulsions. The results of the increase of kinematic viscosity with the increase of surfactant concentration agreed well with Vasistha and Bhar [54].

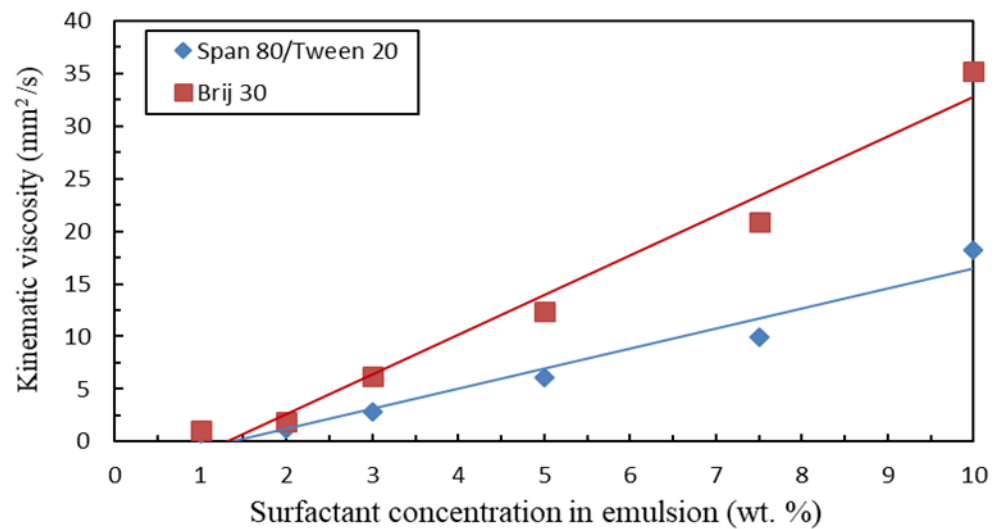


Figure 7. Effects of surfactant concentration on kinematic viscosity of the emulsions with a Tween 20 and Span 80 mixture or Brij 30 surfactant.

The emulsion that was prepared with a 10 wt. % surfactant appeared to have the largest kinematic viscosity for all the emulsions that were prepared with the surfactants of various concentrations ranging from 1 wt. % to 10 wt. %. The precipitating rate of dispersed droplets is inversely proportional to the kinematic viscosity [55]. Hence, the emulsion added with Brij 30 surfactant would have a slower precipitating rate of dispersed phase compared to those with a Tween 20 and Span 80 mixture, hence the higher emulsification stability and kinematic viscosity of the former emulsion. Notably, the results are consistent with a previous study by Lin and Lin [56].

4. Conclusions

Two types of non-ionic surfactants, including polyol and polyethoxylated compounds, with concentrations in the range of 1 wt. % to 10 wt. % were used to produce the emulsion fuel composed of de-ionized water and silicone oil. The emulsion fuel properties, such as kinematic viscosity and mean droplet sizes of the dispersed phase of the silicone oil emulsions, were found to be influenced significantly by the types and concentrations of the surfactants. The major experimental results are concluded in the following.

1. The mean droplet sizes of the dispersed phase of the silicone oil emulsions were reduced with the increase of surfactant concentrations of Brij 30 or the mixture of Span 80 and Tween 20. Slow or fast heating followed by fast cooling significantly decreased the emulsions' mean droplet sizes. However, the mean droplet sizes of the emulsions emulsified with Brij 30 were considerably lower than those prepared with a Tween 20 and Span 80 mixture.
2. The emulsions either added with Brij 30 or Tween 20 and Span 80 mixture subjected to fast cooling were observed to have smaller droplets and a wider range of droplet sizes than those subjected to slow cooling.
3. The emulsions added with Brij 30 surfactant appeared to have larger kinematic viscosity and emulsification stability. The increased surfactant concentrations of either Span 80/Tween 20 or Brij 30 also increased kinematic viscosity.
4. Adding a Tween 20 and Span 80 mixture to the emulsion increased the number of dispersed droplets more than that with Brij 30. The increase of surfactant concentration of Brij 30 or a Span 80 and Tween mixture raised the number of scattered droplets.
5. The silicone oil emulsions by the PIT method were observed to have adequate fuel properties and, thus, are promising alternatives to fossil fuel.

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