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Physical and chemical characteristics of ultrasonically-prepared water-in-diesel fuel: Effects of ultrasonic horn position and water content

Yoshihiro Kojima [a,*], Hiroki Imazu [b], Keiichi Nishida [c]

[a] EcoTopia Science Institute, Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464-8603, Japan
[b] Department of Chemical Engineering, Graduate School of Engineering, Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464-8603, Japan
[c] Department of Chemical Engineering, School of Engineering, Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464-8603, Japan

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A B S T R A C T

An ultrasonic technique was applied to preparation of two-phase water-in-oil (W/O) emulsified fuel of water/diesel oil/surfactant. In this study, an ultrasonic apparatus with a 28 kHz rod horn was used. The influence of the horn tip position during ultrasonic treatment, sonication time and water content (5 or 10 vol%) on the emulsion stability, viscosity, water droplet size and water surface area of emulsion fuels prepared by ultrasonication was investigated. The emulsion stability of ultrasonically-prepared fuel significantly depended on the horn tip position during ultrasonic irradiation. It was found that the change in the stability with the horn tip position was partly related to that in the ultrasonic power estimated by calorimetry. Emulsion stability, viscosity and sum of water droplets surface area increased and water droplet size decreased with an increase in sonication time, and they approached each limiting value in the longer time. The maximum values of the viscosity and water surface area increased with water content, while the limiting values of the emulsion stability and water droplet size were almost independent of water content. During ultrasonication of water/diesel oil mixture, the hydrogen and methane were identified and the cracking of hydrocarbon components in the diesel oil occurred. The combustion characteristics of ultrasonically-prepared emulsion fuel were studied and compared with those of diesel oil. The soot and NO*x* emissions during combustion of the emulsified fuel with higher water contents were significantly reduced compared with those during combustion of diesel oil.

1. Introduction

A mixture of two immiscible liquids for which the droplets of one phase are dispersed within the layer of another continuous phase is called an emulsion. Emulsions have commonly been applied in industry fields of paints, foods, medicine, cosmetics, polymerization, fuel-processing, etc. [1–4]. In general, there are two forms of emulsion such as oil-in-water (O/W) emulsion and water-in-oil (W/O) emulsion. To make stable emulsion formed for the two liquids to be mutually insoluble in each other, it is necessary to apply sufficient agitation to the liquids in the presence of an emulsifying agent.

Recently, many researchers have studied about the application of high power ultrasonic technique to the preparation of materials and synthesis and decomposition of chemical species, because it is possible to enhance the chemical reaction rates and modify chemical and/or physical properties of materials under ultrasonication [5–12]. Ultrasound wave propagation through a liquid causes flow which is called acoustic streaming, in the same direction as the propagation, due to the radiation pressure gradient resulting from the attenuation of sound [13–14]. In addition, high power ultrasonic irradiation to a solution brings about the formation, growth and collapse of cavitation bubbles periodically. The implosive collapse of the cavitation bubbles during the adiabatic compression results in formation of a high temperature and pressure spot, also called "hotspot". Additionally, the collapse and/or formation of the cavitation bubbles cause the formation of high-speed microjets, microstreaming and generation of the shockwave [15–19]. These physical effects such as acoustic streaming, high-speed microjets, microstreaming and shockwave contribute to effective mixing of solution, disruption of immiscible liquid layers and promotion of mass transfer at the liquid–solid interface owing to removal of impurity from solid surface or at liquid–liquid interface region due to an increase in liquid–liquid interfacial area through emulsification of O/W or W/O mixture. Many researchers have reported the preparation of emulsion fuels [20–25] and coal–water fuels [26], solvent extraction of organic

* Corresponding author. Tel.: +81 52 789 3912.
E-mail address: ykojima@esi.nagoya-u.ac.jp (Y. Kojima).

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components from oil shell [27] and synthesis of biodiesel fuel by ultrasonic methods [28–29]. Several researchers have studied about the application of ultrasonic chemical effects which occur in/around hotspots, to cracking of chemical components in liquid fossil fuel. Price has reported that chemical components in diesel oil were cracked under ultrasonication [30].

In this study, an ultrasonic technique was applied to preparation of two-phase water-in-oil emulsion fuel in the presence of an emulsifying agent. Influence of position of a horn tip emitting ultrasound into sample solution, sonication time and water content on the emulsion stability, viscosity, diameter distribution of fine water droplets and water surface area was investigated in water/diesel oil/surfactant mixture. The combustion characteristics of the emulsion fuel prepared under ultrasonication were studied and compared with those of diesel oil. In addition, sonolysis of oil components in water/oil system without an emulsifying agent was investigated.

2. Experimental

2.1. Reagents

Diesel fuel supplied to the public was purchased from a gas station. Span80 ($C_{24}H_{44}O_6$) was purchased from Wako Pure Chemical Industries, Ltd. Ion-exchange water was employed.

2.2. Ultrasonic apparatus

Fig. 1(a) shows a schematic diagram of the experimental apparatus. A horn-type (Degetal Sonifier S-250D, Branson Ultrasonics Co.) was used to emit ultrasound. The frequency of ultrasound was 28 kHz and electronic input powers were 20 and 100 W. The cylindrical reaction vessel (ID 100 mm) containing the sample mixture solution was immersed in a water bath and the mixture solution was kept at a constant temperature of 298 ± 1 K. The amount of the mixture solution was about 500 ml and the liquid height in the reaction vessel was hence about 70 mm. Cracking test of saturated carbon components in water (5 ml)/diesel oil (45 ml) mixture or diesel oil (50 ml) under ultrasonication was performed in the stainless steel cylindrical vessel with the concave bottom, as shown in Fig. 1(b).

2.3. Emulsification

Span80 was used as a surfactant to improve the stability of the emulsion. Span80 was added into the diesel fuel/water mixture solution and the surfactant content was 2 vol%. The water content in the mixture solutions was 5 or 10 vol%.

2.4. Combustion test

The stainless steel cylindrical furnace equipped with a commercial burner (SG-S Series, Kato Tekko burner factory) was employed for combustion experiments of diesel fuel and emulsified fuels prepared by ultrasonic treatment. Fuel with swelled air used as oxide agents was supplied into a furnace. For all combustion tests, the fuel volumetric flow rate was 2 L/min and the fuel equivalence was adjusted to 0.6 by changing the air volumetric flow rate. The fuel was atomized from the atomization nozzle set in the center of the burner, at the pump pressure of 0.7 MPa. The stainless steel cylindrical furnace has an inner diameter of 100 mm and a length of 600 mm. At outlet of the furnace, a sampling probe was set to take the exhaust gas. R type thermocouple (Pt/Pt-Rh13%, strand diameter ∅ 0.1 mm) connected with a temperature recorder (NR-500, NR-TH08, Keyence Corp.) and PC was set at center axis of the furnace in order to measure temperature at 10 points in the furnace.

2.5. Measurement

2.5.1. Ultrasound power measurement

The sonochemical reactor was equipped with a K type thermocouple (Copper and constantan, Omega Engineering Inc.) which is connected with a temperature recorder (NR-500, NR-TH08, Keyence Corp.) and PC. The ultrasound power, P_{US}, dissipated to the reaction system was calculated from the following equation:

$$P_{US} = M_{US} \cdot C_{PUS} \frac{\Delta T}{\Delta t} \tag{1}$$

where M_{US}, C_{PUS} and $\Delta T/\Delta t$ denote the water mass, specific heat of water at constant pressure and rate of temperature increase, respectively.

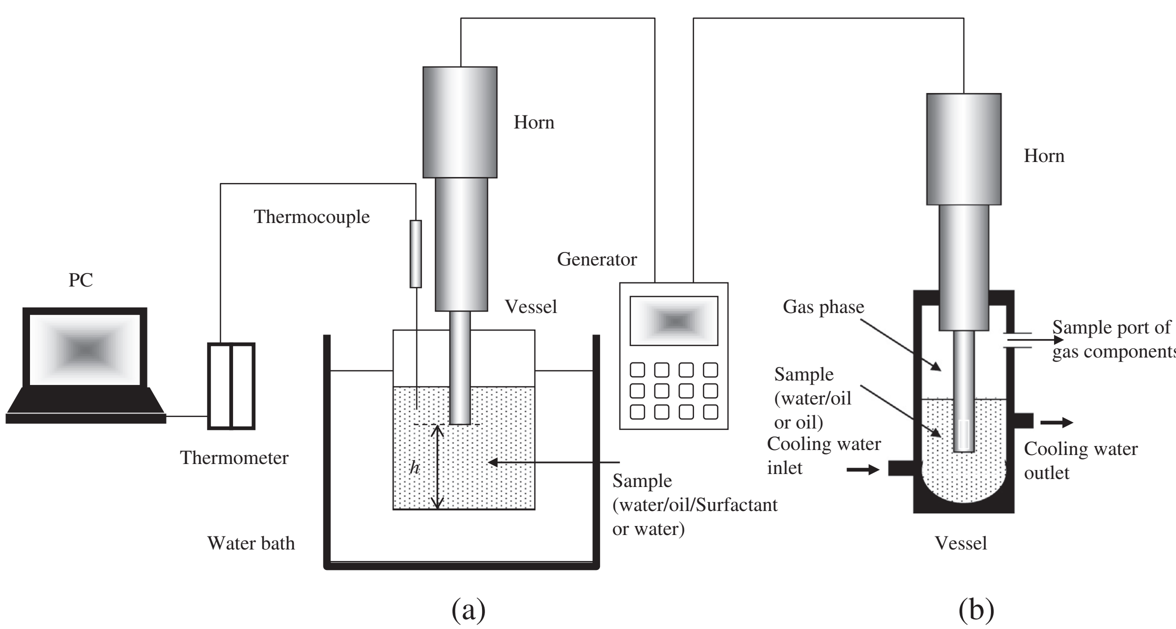

Fig. 1. Schematic diagram of the experimental apparatuses for preparation of emulsion fuel and cracking test of diesel oil.