Frequency Analysis of Water-Vegetable Oil Emulsion Produced by Taylor-Couette System with Small Aspect Ratio Using Ultrasonic Doppler and Attenuation Method

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The emulsification method is not only one of the potentially effective techniques to reduce fossil fuel consumption but also exhaust emission from diesel engines. Water-in-Oil (W/O) emulsified fuel is reported to reduce the emissions of NOx, SOx, CO and particulate matter (PM) caused by a decrease in combustion temperature and a micro explosion in combustion. However, the emulsified fuel shows non-Newtonian properties called pseudoplastic flow as water content ratio increases. Since a viscosity of pseudoplastic flow decreases with increasing shear rate, the W/O emulsified fuel causes clogging of fuel injector, decrease of combustion efficiency due to deterioration of fuel spray in high water content ratio. It is important to know a state of flow transition of the emulsified fuel in mixing conditions. In this study, we evaluated W/O emulsified fuels using ultrasonic measurement, produced 10 %, 20 %, 30 % water-vegetable oil emulsion at 300-800 rpm with a Taylor-Couette reactor. We measured velocity profiles and attenuation of echo at every 100 rpm utilizing the ultrasonic Doppler method and echo intensity measurement. As a result, transitions of the velocity profiles and the echo attenuation were different in each water content ratio.

Keywords: Emulsified fuel, Ultrasonic measurement, Taylor-Couette flow

1. Introduction

Emulsified fuel is a type of emulsion in which water and fuel oil are emulsified and mixed, causing a micro explosion when the superheat limit of water is exceeded during combustion. Emulsified fuel is researched mainly as an alternative fuel for diesel engines and marine boilers [1] . Mixing with water not only reduces the fuel consumption rate but also reduces the carbon monoxide (CO) and particulate matter (PM) emissions because the micro explosion causes the contact area between the fuel droplets and air to increase, approaching complete combustion. In addition, there is a report that NO_X emissions are reduced due to a decrease in combustion temperature due to the evaporation of water contained in the fuel [2]. However, if water and fuel oil are used in a phase-separated state, there are problems such as failure of the internal combustion engine and the effect of reducing exhaust gas due to micro explosion cannot be obtained. Therefore, the stabilization of fuel is an important issue for practical use. The stability of emulsified fuel is obtained by preventing creaming, in which water droplets in the dispersed phase settle and separate into layers due to the density difference from fuel oil in the continuous phase, and aggregation and coalescence of droplets adhering to each other. In this study, we focused on measurement using the properties of ultrasonic waves. Ashrafi et al. [3] and Yektapour et al. [4] are studying pseudoplastic fluids in rotating flow and are proceeding with physical elucidation. Ultrasonic has the property of being reflected and attenuated at the interface of media with different acoustic impedances and is used to measure the volume concentration of suspended particles [5]. When these methods are applied to emulsions, the particle diameter does not affect the number revolutions in the case of solids but in the case of droplets, it is expected that the diameter changes because of the shear changes with the number of revolutions. In this study, the droplet diameter of the emulsion was measured by ultrasonic attenuation to evaluate the stability of the emulsified fuel. The challenge for practical use as an emulsion fuel generator is to produce an emulsion that does not separate for a long time. If the TCF stirrer can be mounted directly on the vehicle body, the emulsion can be injected into the internal combustion engine without separation immediately after stirring. However, it is difficult to produce an emulsion with a fine droplet diameter by mechanical stirring such as TCF stirring as compared with the membrane emulsification method. Therefore, we focused on the production of emulsion by a low aspect ratio TCF stirrer that can be mounted directly.

2. Experimental setup and conditions

Figure 1 shows a Taylor-Couette Flow (TCF) generator. The boundary conditions of the equipment were fixed at the upper and lower ends. The dimensions of each part of the coaxial double cylindrical container were as follows: inner cylinder radius R_{in} = 50 mm, outer cylinder radius R_{out} = 75 mm, and height H = 75 mm. From this, the gap between the inner cylinders was set to $d = R_{\mathrm{out}} - R_{\mathrm{in}}$ = 25 mm and the radius ratio $\eta = R_{\mathrm{in}} / R_{\mathrm{out}}$ = 0.667. The aspect ratio becomes low when the aspect ratio $\Gamma = H / d$ = 3. The rotation speed can be set in the range between 10 and 800 rpm by a DC servo motor mounted on the inner cylinder and set by the driver. The rotation speed can be changed in 1 rpm increments by turning the driver dial. An ultrasonic transducer (TDX) that emits ultrasonic waves was installed at a position 12.5 mm from the outer circumference of the inner cylinder at the upper end of the device, and the axial ultrasonic echo intensity obtained from the emulsion was measured. Table 1 shows the experimental conditions of this experiment. In this experiment, an emulsion consisting rapeseed oil and ion exchanged water was used as the working fluid. The water content ratio is 10, 20 and 30 %. The working fluid temperature was controlled at 20 ℃ using a thermostat.

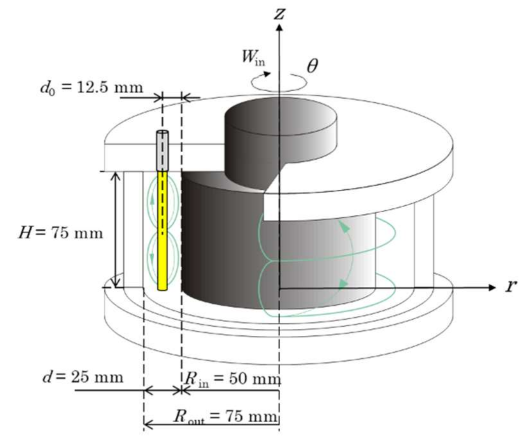

Figure 1: Schematic diagram of Taylor-Couette Flow

Table 1: Experimental conditions

Boundary conditions	Fixed
Water content ratio	10 , 20, 30 Vol. %
Rotation speed	300 – 800 rpm
Rapeseed Oil density	920 kg/m^3
Water density	998 kg/m^3
Rapeseed oil sound velocity	1482 m/s
Water sound velocity	1482 m/s
Temperature	20 ℃
Basic frequency	8 MHz
Gain	40 mV/Div

3. Methods

The working fluid was ion exchanged water and rapeseed oil. After filling in the TCF generator, the emulsion was formed by rotating the initial rotation speed from 300 rpm. The rotation speed is set every 100 rpm from the initial rotation speed, and under each condition, ultrasonic measurement is performed after stirring for 20 minutes. The resulting echo is shown in figure 2(a). The vertical axis shows the echo intensity, and the horizontal axis shows the normalized distance z/H by dividing the distance from TDX by the device height H = 75 mm. The region with a normalized distance z/H = 0.0 to 0.1 shown in figure 2(a) was excluded because it is a near field where the sound pressure is unstable [7]. Also, the normalized distance z/H = 0.5 or later was excluded because it is difficult to confirm the echo due to the effect of diffusion attenuation. Figure 2(b) shows the echo intensity waveform obtained by averaging the measured echo data for 30 times and taking the absolute value. The vertical axis shows the echo intensity, and the horizontal axis shows the normalized distance z/H. Ultrasonic attenuation is defined as a distance-dependent exponential function by Weser et al.[8] as follows,

$$I = \beta e^{-\alpha z/H} \quad (1)$$

where, if the attenuation coefficient is α and the dimensionless distance from TDX is z/H.

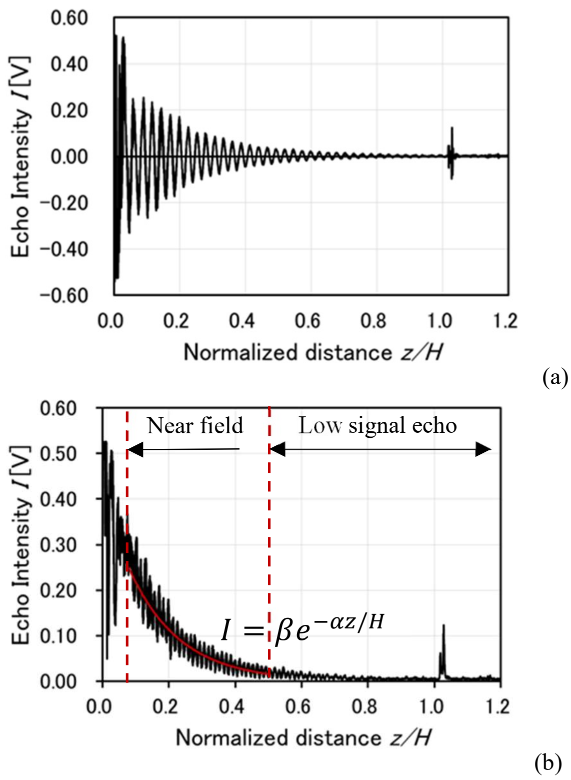

Figure 2: Typical echo from a stirred emulsion (a) raw echo signal, (b) absolute and averaged echo calculated for 30 single measurements

4. Results and discussion

Figure 3(a) shows the measurement results of the ultrasonic decrement coefficient for water content ratio 10%, 20%, and 30% emulsions. From figure 3(a), it is considered that there is no correlation between the water content ratio and the ultrasonic decrement coefficient. However, looking at the decrement coefficient for each rotation speed of inner cylinder, the decrement coefficient increased as the rotation speed increased. Figure 3(b) shows a graph in which the horizontal axis of figure 3(a) is the number of revolutions. As can be seen from figure 3(b), the decrement coefficient increases with increasing rotational speed at any water content ratio. In addition, since the process of increasing the decrement coefficient is different at a water content ratio of 30%, it is expected that the flow state will be different at a water content ratio of 30% than at 10 and 20%. Figure 4, 5 and 6 show the results of color plot display of time-series velocity distribution

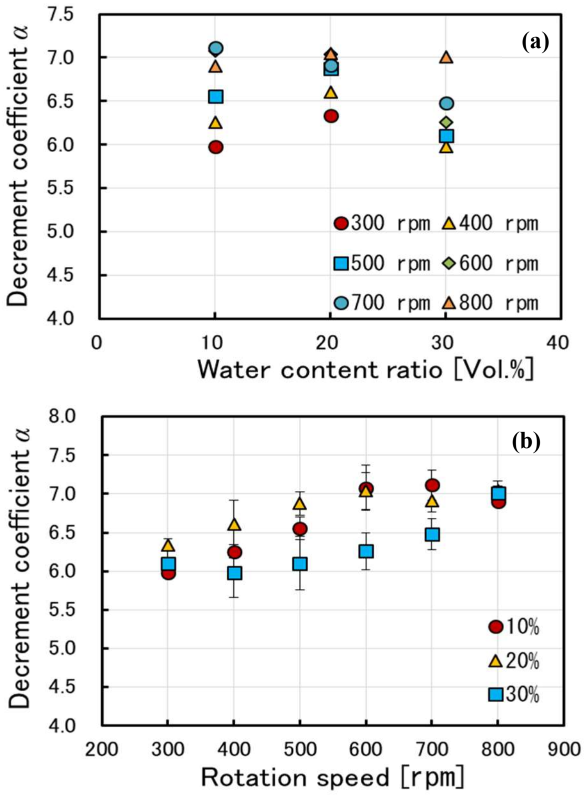

Figure 3: Decrement coefficient in each water content ratio and rotation speed, (a) α versus water content ratio, (b) α versus rotation speed

data obtained by measuring the water content ratio 10, 20 and 30% emulsions using an ultrasonic velocity profiler (UVP). In these figures, the vertical axis is the normalized distance of each measurement position *z* at the height *H* of the entire measurement section, and the horizontal axis is the time. *z/H* = 0.00 indicates the device upper plate (TDX installation position), and *z/H* = 0.50 indicates the device intermediate position. The figure shows the velocity component in the axial direction, the velocity from the bottom plate to the top plate of the device is positive, and the color plot shows the magnitude of the velocity. Compering figure 4, 5, and 6, the 10 and 20% emulsions have similar flow velocity distribution oscillations at 500 rpm and 600 rpm. In the case of Newtonian fluid, the low aspect ratio flow is TVF below *Re* = 700 and WVF with one fundamental frequency from *Re* = 700 to 1000. When *Re* = 1000 or more, modulated wavy vortex flow (MWVF) has multiple fundamental frequencies. Looking at the velocity distributions from Fig. 4 to 6, there is a flow that oscillates periodically at *Re* = 900 for 10% emulsion and *Re* = 700 for 20% emulsion. This is in the region of wavy vortex flow (WVF) under the conditions at this time, but the magnitude and period of the amplitude are qualitatively consistent with *Re* = 1100 in the Newtonian fluid. Therefore, the flow was the same as in the high viscosity region with a low Reynolds number. The results of frequency analysis are shown Figures 5-7. Figures show water content of 10%, water content of 20%, and water content of 30%. The x-axis is *f**, the y-axis is *Re*, and the z-axis is the frequency component. The power spectrum

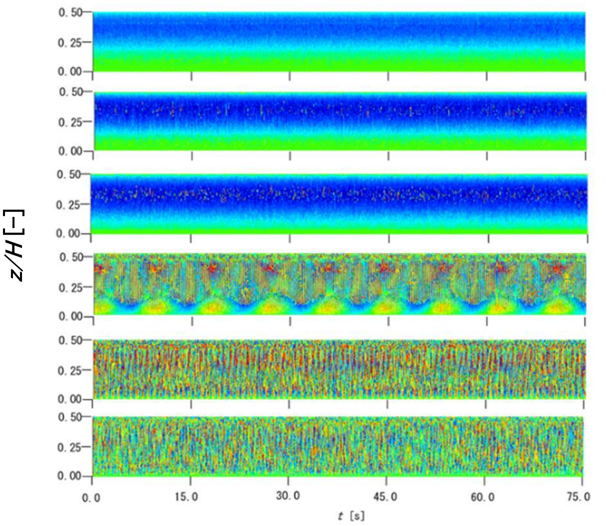

Figure 4: Time development velocity profile at 10% W/O emulsion using UVP

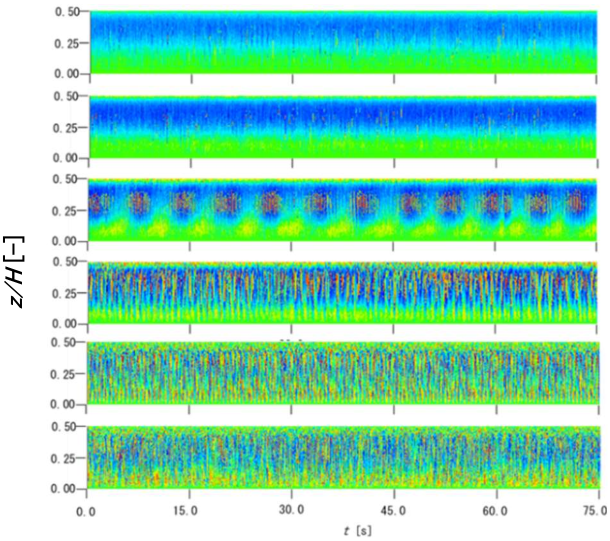

Figure 5: Time development velocity profile at 20% W/O emulsion using UVP

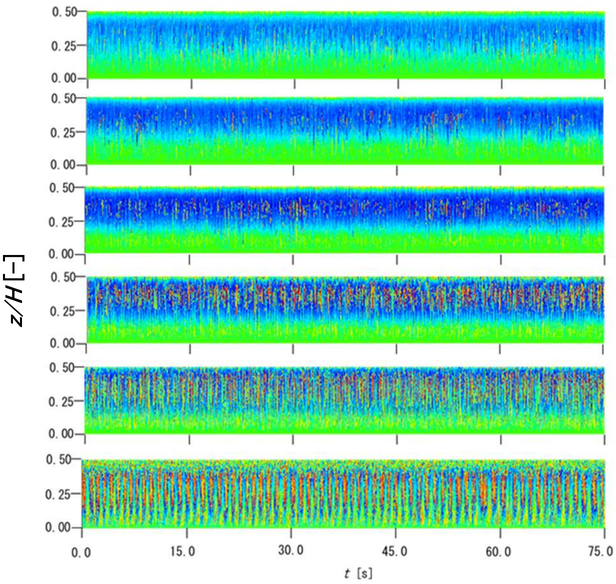

Figure 6: Time development velocity profile at 30% W/O emulsion using UVP

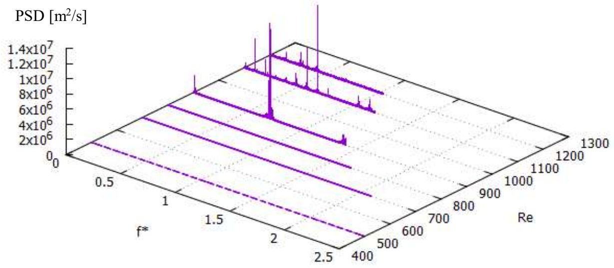

Figure 7: Space-averaged power spectrum density of 10% emulsion

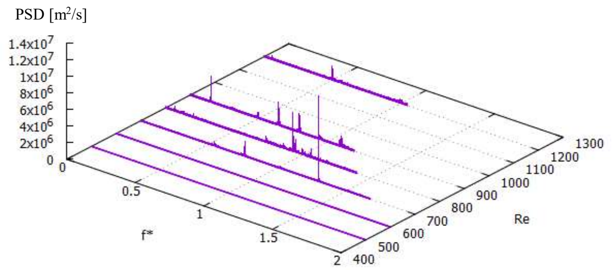

Figure 8: Space-averaged power spectrum density of 20% emulsion

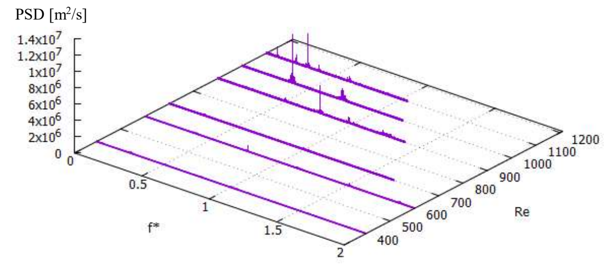

Figure 9: Space-averaged power spectrum density of 30% emulsion

density (PSD) [m^2/s], which indicates the strength of, is shown. As a result of Figure 5, it is said that a wave Taylor vortex flow in which the cell vibrates periodically is generated at any water content [7], and the peak of the spectrum is detected from Re = 700 to 1000. In Figs. 5-7, *Re* = 900, peaks are detected near f^* = 0.7 at water content of 10 and 30%, but f^* = 0.15 and 0.65 at 20%, 0.8 and multiple peaks were confirmed. Emulsion fuel becomes more viscous as the water content increases and exhibits pseudoplastic flow [8]. In the case of pseudo-plastic flow, the viscosity of the fluid decreases as the shear stress increases. Therefore, in an emulsion with a water content of 20%, the decrease in viscosity due to the pseudoplastic flow state is greater than the increase in viscosity due to the increase in water content. It is considered that the effect was strong, *Re* was higher than that of the water content of 10 and 30% emulsion, and the fluid state was different. In the low aspect ratio TCF using Newtonian fluid as the working fluid, the spectrum was observed near f^* = 2.0 from *Re* = 700 to 1000. On the other hand, the spectrum peaks are seen at f^* = 0.70 for the 10% emulsion, f^* = 0.15, 0.65, 0.80, 0.93, 1.30 for the 20% emulsion, and f^* = 0.38 and 0.76 for the 30% emulsion. It has been reported that the vorticity is changed compared to non-Newtonian fluids and Newtonian fluids [9]. From the above, it is considered that when a non-Newtonian fluid such as an emulsion is used as a working fluid, a Taylor vortex vibration different from that of the Newtonian fluid is generated. Comparing the cases of Newtonian fluid and pseudoplastic fluid from these results, it is considered that the pseudoplastic fluid vibrates at a lower frequency even if it is the same WVF. In addition, when comparing the emulsion Re900, a single peak was detected in the 10% emulsion and the 30% emulsion, but multiple peaks were confirmed in 20%. It is considered that the decrease in viscosity during stirring of the 20% emulsion had a stronger effect than the increase in viscosity due to the increase in water content, and the Reynolds number increased because it became a fluid state like MWVF.

5. Summary

As a result of measuring the ultrasonic attenuaion coefficient at the water content ratio of 10, 20 and 30%, the following findings were obtained.

- No change was observed in the ultrasonic decrement coefficient due to the change in water content ratio.
- The ultrasonic decrement coefficient tended to increase as the inner cylinder rotation speed increased.
- According to the velocity distribution, in the 10 and 20% W/O emulsions, the oscillation of the flow velocity distribution occurs at 600 rpm and 500 rpm, and the cycle is similar, but in the 30% W/O emulsion, such oscillation was not appeared.

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