Dispersive Performance of Underwater Injection of Dispersant to Heavy Fuel Oil

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ABSTRACT

The National Maritime Research Institute started 5 year research project on the establishment of synthetic counter-measures against the discharge of oil and hazardous fluid substance from 2011 to 2015. The main purpose of this project is to produce the tool for the environmental risk assessment of the oil discharge from vessels which sank due to the marine accident. The element technologies as the counter-measure against the discharged oil will also be developed in the project.

The element technology as sub-surface application of dispersant for counter-measures will be introduced at the poster session. The first large-scale application has been carried out during the Deepwater Horizon incident in gulf of Mexico in 2010. The experimental set-up consists of rectangular water tank (0.8mx0.8mx3.0m) connected to the oil tank and dispersant tank. The heavy fuel oil was used. Both oil and mixed sample of oil and dispersant have been discharged from the nozzle into the water tank. The video for the behavior of oil and mixed sample has been analyzed by defining the concentration of black and white color. The video has been taken by the high resolution camera. The concentration of 8 different steps between black and white was set in the analysis. The dispersed oil has particular color when dispersed in water and too much dispersant becomes clouded because the dispersant reacts to water. The concentration change has been related with the dispersive performance. The rising-up velocity was also analyzed by PIV (Particle Image Velocity) method so as to ensure the effect of the dispersive performance. The distribution of oil droplets has also been measured and analyzed

The various percentage of dispersant has been compounded into mixed heavy fuel oil. 1%, 5% and 10% dispersant oil ratio (DOR) has been tried in the experiment. The dispersive area and rising-up velocity after injection of both oil and mixed sample have been compared among them. The dispersive area and rising-up velocity due to difference of DOR has been discriminated. Those parameters can be an index of evaluating the dispersive performance.

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INTRODUCTION

The National Maritime Research Institute started 5 year research project on the establishment of synthetic counter-measures against the discharge of oil and hazardous fluid substance from 2011 to 2015. The main purpose of this project is to produce the tool for the environmental risk assessment of the oil discharge from vessels which sank due to the marine accident. The element technologies as the counter-measure against the discharged oil will also be developed in the project. (Miyata,2012)

The sub-surface application of the dispersant to reduce the environmental damage due to oil discharge is one of the counter-measures. The investigation of element technology as sub-surface application of dispersant for counter-measures has been carried out. The first large-scale application has been carried out during the Deepwater Horizon incident in gulf of Mexico in 2010. However, the effect of the dispersant has not securely been validated in many aspects. The laboratory tank for dispersant spray in water has been set up. The PIV and PTV method for analyzing the behavior of the oil and dispersant have been applied using the high resolution video camera. The effect of dispersant on the discharged oil will be investigated by the analysis.

The experimental set-up consists of cylindrical water tank (0.8mx0.8mx3.0m) connected to the oil tank and dispersant tank. The heavy fuel oil was used. The oil has been discharged from the nozzle into the water tank while the dispersant being injected. The behavior of oil and dispersant has been analyzed by defining the concentration of black and white color. The video has been taken by the high resolution camera. The concentration of 8 different steps between black and white was set in the analysis. The dispersed oil has the particular color when dispersed in water, because the dispersant reacts to water before reaching oil . The change of concentration has been related with the dispersive performance.

The various percentage of dispersant has been compounded into mixed heavy oil. 1%, 5% and 10% dispersant oil ratio (DOR) has been tried in the experiment. The dispersive area and flow velocity after injection of dispersant has been compared among them. The flow velocity was analyzed by PIV (Particle Image Velocity) method. The dispersive area due to difference of DOR has been discriminated.

Model experiment in water tank

The water tank (0.8m x 0.8m x 3.0m) was used in the experiment for the sub-surface application of dispersant. First the mixed sample of oil and dispersant has been discharged from the nozzle installed at 0.5 m above the bottom of the tank. The diameter of nozzle is 19mm. Table 1 shows the DOR in weight percentage of the mixed sample. There are 4 kinds of DOR such as 0%, 1%, 5% and 10%. The tank for both oil and dispersant were connected to the water tank through the joint pipe and flexible hose. There are 2 kinds of flow rate conditions such as 1.5 and 6.0 liter/min. The flow rate was controlled by the gear pump, needle valve and straight cock. 2 high resolution CCD cameras with black and white display (1392 x 1040). The image sensor is 6.45μm x 6.45μm. Those 2 cameras have been synchronized by the control software of the analyzing system and the images of 2 area such as the neighborhood of the nozzle and whole of the tank were selected for the analysis. A heavy fuel oil was used and its physical properties of oil and dispersant are shown in Table 2. The instrument for analyzing the particle size distribution by the laser diffraction method was also used to measure the size of the dispersed oil.

Image analysis method

The analysis of the speed of rising up of the mixed sample and dispersed area after discharging of oil into water has been carried out. The software of Library Co. Ltd. for the analysis of the behavior of the sample has been used. The PIV (Particle Image Velocimetry) method was used as the image processing technique for measuring the rising speed of the mixed sample. The vector coordinate of the particle has been measured without binarization process. The mean velocity for the sampling area has been obtained. The area, coordinate and trajectory of concentration bodies have been analyzed by measuring the time history of concentration variation. The dispersed area has been evaluated by color variation using 8 classification of luminance variation in the experiment.

Table 1. DOR in weight of sample

sample No.	weight(g)			DOR (W%)
	A heavy fuel oil	dispersant	sum	
1	17.4	0.9	18.3	5
2	17.9	1.7	19.6	9
3	19.4	3.0	22.3	13
4	20.2	5.0	25.2	20

Table 2. Physical property of oil and dispersant

	dynamic viscosity (CSt)	density (kg/m3)
A heavy fuel oil	4.28	0.857
dispersant	3.94	0.803

Table 3. DOR and n value of distribution factor for Rosin-Rammler distribution

	density	viscosity (cSt,20deg)	DOR(%)			
			5	9	13	20
A heavy fuel oil	0.86	4.28	6.72	1.88	1.42	1.36
heavy fuel oil	0.976	1850	DOR(%)			
			14	19	22	30
			3.86	4.02	3.73	2.23

Experimental results

There are 4 kinds of DOR such as 0%, 1%, 5% and 10% for the flow rate of both 1.5(ℓ/min) and 6.0(ℓ/min). Figure 1 shows the speed of rising up of the sample for the 2 cases of flow rate. The speed of rising up of both cases for 0% of DOR is the same. This means that the effect of the initial speed from nozzle is small. The initial speed of 2 cases of flow rate is 0.35 m/sec and 0.09 m/sec respectively. The larger the DOR is, the smaller the speed of rising up becomes. In general, the smaller the diameter of the fluids particle becomes, the smaller the speed of rising up becomes. This means that if the oil is dispersed, the speed of rising up is reduced. When DOR becomes 5%, the speed of rising up drastically decreases. It is considered that the mixing energy at the outlet of the sample becomes larger due to the large initial speed from the nozzle and thus the dispersion effect was increased. Figure 3 also shows the speed vector of the flow for each case. Figure 4 shows the dispersion area of oil. The larger DOR is, the larger the dispersion area becomes. This means the dispersion was accelerated due to the effect of dispersant. This tendency appears more clearly in the case of larger flow rate. (Miyata, 2013)

The particle size distribution for each DOR from 5% to 20% was measured by the analyzer using the principle of laser diffraction (SALD-7100, Shimadzu). Figure 5 shows the results of each sample. There are 3 samples for each DOR. The droplet size distribution was computed from the Rosin-Rammler type distribution. This means that the fraction of total oil and dispersant volume contained in droplets with diameter less than d given by the equation

$$V(d) = 1 - \exp\left\{-2.996\left(\frac{d}{d_{\max}}\right)^n\right\} \qquad (1)$$

The spreading component n in equation (1) was calculated as shown in Table 3 for an arithmetic average of data by the regression analysis. As for the 5% of DOR, the data were scattered due to an instability of mixed sample. The other data were not so much scattered. Another much more viscous heavy fuel oil was also taken as a sample as shown previously mentioned from 14% to 30% of DOR. The value of n for the latter case was larger than those for A heavy fuel oil. The spreading component n for A heavy fuel oil and much heavier fuel oil was calculated as 6.72 and 3.86 respectively in case of 5% of DOR for an arithmetic average of data by the regression analysis.

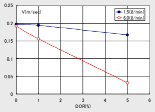

Figure 1. Change of rise-up velocity with DOR

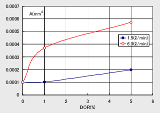

Figure 2. Change of dispersed area with DOR

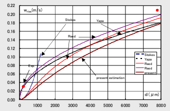

Figure 7. Experimental results and estimation of rise velocity

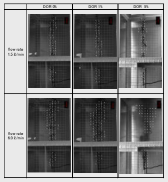

Figure 3. Results of analysis for velocity vector of the mixed sample

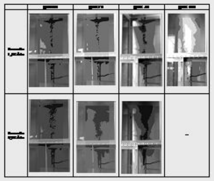

Figure 4. Results of analysis for concentration of the mixed sample

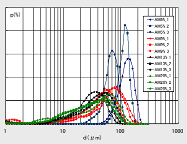

Figure 5. Particle size distribution of A heavy fuel oil

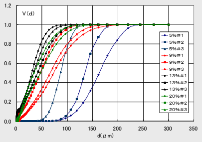

Figure 6. Cumulative volume particle distribution of A heavy oil

Johansen(2002) described the method to estimate the droplet size distribution based on the release conditions. The maximum droplet size is related to the exit diameter and dimensionless Weber number in which the exit velocity, density and interfacial tension are included.

$$W_e = \frac{v_0^2 d_0 \rho_w}{\sigma} \qquad (2) \qquad\qquad d_{\max} = k d_0 \left(\frac{v_0^2 d_0 \rho_w}{\sigma}\right)^{-0.6} \qquad (3)$$

where ρ is density of continuous phase, v_0 is exit velocity, d_0 is exit diameter, and σ is interfacial tension.

The value of coefficient k is expressed in the equation (3). Karabelas(1978) established empirically that the coefficient k is 4 from the pipe flow experiments as for the mist flow case. On the other hand, k=20 was chosen to match the observation from the DeepSpill experiment (Johansen, 2002) as for an oil jet case.

The sample in this experiment should be close to the former case, because the flow becomes mist due to dispersive effect. The coefficient k was calculated as 6.5 by the regression analysis.

Reed(2003) estimated the wise velocity of oil droplet by the following equations as equation (1) and (2) for small droplets (Re<1) and large droplets (Re>1000). w_1 is so called Stokes velocity. Reed added the interpolation scheme in order to account for droplets of all sizes as shown in equation (3). In these equation, d is the diameter of droplet and v is the dynamic viscosity of fluid, while g' is the reduced gravity. ρ_o and ρ_w is the density of particle and fluid respectively.

$$w_1 = \frac{d^2}{18\upsilon} g' \quad (4) \qquad w_2 = 1.8\sqrt{dg'} \quad (5) \qquad w_3 = \frac{1}{\frac{1}{w_1} + \frac{1}{w_2}} \quad (6) \qquad g' = g\left(1 - \frac{\rho_o}{\rho_w}\right) \quad (7)$$

The rise velocity of droplet can generally be shown as the following equation using the drag coefficient C_D.

$$w_{rise} = \sqrt{\frac{4}{3}\frac{gd}{C_D}\left(1 - \frac{\rho_o}{\rho_w}\right)} \qquad (8)$$

Yapa estimated the rise velocity for the droplet with size larger than the defined critical size using C_D=0.5.

$$w_2' = \sqrt{\frac{8}{3} g' d} \qquad (9)$$

In the range between 1 and 10^4 of Reynolds number Re, C_D can be shown from equation (8) to (10) as the following equation (12).

$$C_D = \left(0.55 + \frac{4.8}{\sqrt{\mathrm{Re}}}\right)^2 \quad (10) \qquad R_e = \frac{w_{rise} d}{\upsilon} \quad (11) \qquad w_{rise} = \left(\frac{\sqrt{A_1^2 + 2.2\sqrt{A_2}} - A_1}{1.1}\right)^2 \quad (12)$$

where, $A_1 = \frac{4.8}{\sqrt{\frac{d}{\upsilon}}}$, $A_2 = \frac{4}{3} dg'$

Figure 7 shows the experimental results of the rise velocity for 2 kinds of flow rate (1.5 and 6.0 liter/min) and above mentioned estimated results. There is a big difference between experimental results and estimated results, because the estimated rise velocity is for the only one droplet in the fluids instead of group of droplets.

Conclusion

The experiment for the sub-sea injection application of dispersant has been carried out using the vertical water tank with 3m depth. The mixed sample of oil and dispersant with DOR (dispersant and oil ratio) was used in order to investigate the behavior of the dispersed oil. The rising rate and dispersion area of the sample have been focused in the experiment. It was found that those characteristics are related to the dispersive performance of dispersant. Further, the particle size distribution of dispersed oil has been investigated and the characteristic coefficients concerning the droplet size together with the estimated rise velocity has been obtained.

Acknowledgement

This research has been carried out as the cooperative research between National Maritime Research Institute and University of Tokyo. The work has been supported by JSPS KAKENHI Grant Number 24360364.

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