Novel oil skimmer using bubble barrier and water jet suction — Prototype design and its tank test

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Abstract

This paper presents a new and innovative oil skimming device, which combines a bubble barrier and a water jet suction. The basic design philosophy of this device is based on the following two principles: (1) no oil-water separation on the water surface, and (2) no damming nor enclosure of oil by solid elements. By adopting these two principles, the device can have a very simple structure, light weight, which is quite different from many conventional oil skimmers, can solve many problems that the conventional oil skimmers suffers from, such as poor responsibility to the high viscosity oil or low maneuverability of the vessel trailing the skimmer with high water flow resistance. The author prototyped an experimental model and conducted experiments to confirm the effectiveness of these principles. It was found that the combination of the bubble barrier and the high-pressure water jet suction was effective for oil recovery to give a future vision of the oil recovery system.

Key words

oilspill response, mechanical recovery, bubble barrier, water jet suction

1. Introduction

Although marine pollution by oil spill incident has been decreased over several tens years, it is still current issue. Oil recovery is one of the main countermeasures to the marine oil pollution (M.Fingas,2012), however, its effectiveness is sometimes limited since the mission is very sensitive to physical properties of the spilled oil, viscosity in particular, as well as weather and sea conditions.

In terms of actual equipment, many types of mechanical skimmers such as weir, drum , brush ,belt and grooved disc, have been developed and supplied to the market so far (World catalog,2017), but the basic principles has not changed for a long time , and no device has emerged yet that is truly innovative or can be called the final solution. Although various methods have been tried, most machines use solid elements to contain or pump up oil. When attempting to recover high-viscosity oil with such a device, the oil adheres to the surface of the element both inside and outside the device, resulting in extremely low oil recovery efficiency. On the other hand, for oil skimmers installed on oil recovery vessels, the drag force generated during towing is a major problem for maneuverability. For overcoming these problems, this study introduced new principle concepts, which are:

(1) No separation of oil and water at the water surface.
(2) No damming nor enclosure of oil by solid elements.

These two basics are derived based on the author's previous experience and past research results.

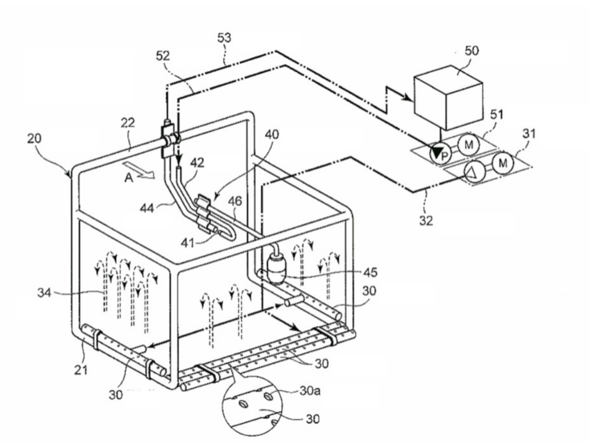
With regard to the rule (1), when transporting highly viscous oil alone in a pipe for instance, a very large pressure loss is generally generated. However, by mixing it with water, the fluidity in the pipe is dramatically improved (JVOPS,2003) since the added water forms a lubricating layer between the oil and the solid wall (Core Annular Flow I.FUJITA,2013). It is more reasonable to perform oil-water separation by discharging excess water in the collection tank rather than in the oil recovery unit. Thus, an oil suction with a high-pressure water jet was adopted in this study. The water jet suction is one of the good option to suck high-viscosity oil (M.Tatsuguchi,2004), because of its high suction power, mechanical simplicity and robustness. Moreover, it also has an advantage in a pipe line flow. The water jet suction has its driving water form a CAF in the pipe line spontaneously to decrease friction loss caused by the direct contact of oil to the pipe wall.

With regard to the rule (2), in general, when a solid plate is placed in water, a drag force proportional to the product of the area facing the flow and the square of the flow velocity is generated. This force can be much greater than imagined, limiting the high speed movement of the vessel with the skimmer in tow. An alternative method which does not generate drag force is desired. For this purpose, a bubble barrier was introduced in this study. In recent years, the value of bubble barriers has been recognized again (T. Mcclimans,2012), and its application to drifting oil has been developed for various purposes (I.FUJITA,2016). In this research, as an application to oil skimmer, the bubble barrier is intended to collect oil floating on the water surface and hold it in a certain area instead of the conventional solid oil boom.

In this study, in order to verify the validity of the above concepts, a prototype skimmer model was made and experimentally evaluated with respect to oil containment performance and oil recovery performance.

2. Prototype Model

In order to evaluate the effectiveness of a combination of the bubble barrier and water jet suction in the oil recovery, the author prototyped several types of scale model for a large scale tank test. A schematic drawing of the concept model is shown in Fig.1 (I.Fujita,2020) and an external view of the latest prototype is shown in Fig.2. As the figure shows, the concept machine basically consists of only pipe elements and scarcely use plate-like members to block the flow passing the skimmer, it has a very simple structure so as to be called a skeleton. The latest model shown in Fig.2, which shares the basic structure to the concept model, has, however, some modification on some parts: panels on the sides and integrated structure of the structure member and the pneumatic system. The side panels, which are placed parallel to the flow, they do not create large resistance to the water flow but enhances the side bubble efficiency. The integrated structure provides light weight feature to the skimmer.



Item #	Description
20	Frame
30	Air diffuser pipe
30a	Diffuser hole
30	Air Blower
40	Ejector unit
41	Suction port
42	Water feed pipe
44	Recovery pipe
45	Float
50	Oil-water separator/Recovery tank
51	Water pump unit
52	Water feed hose
53	Recovery hose

Figure 1 Schematic of a new skimmer.

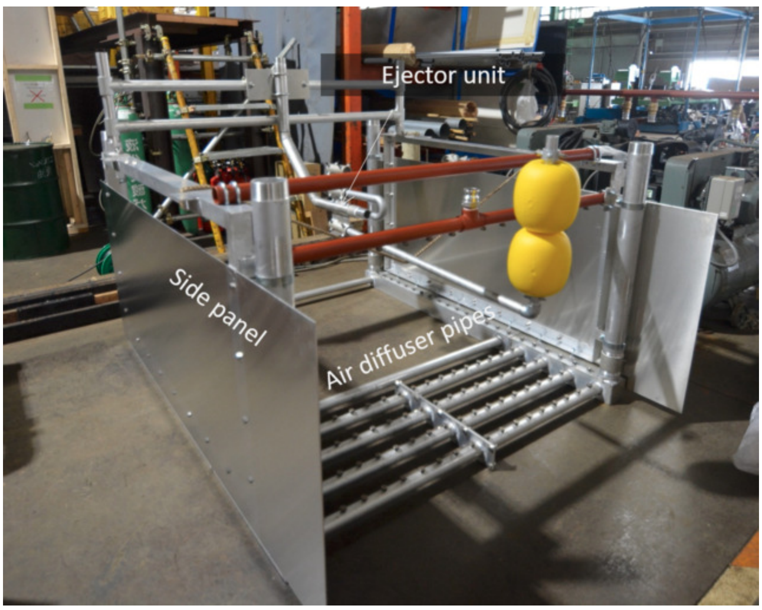


Figure 2 A snapshot of a new skimmer

Air diffuser pipes are installed on the stern and the both sides of the skimmer. This "U-shape" bubble barrier blocks the oil to pass through the device and also gathers it laterally to the suction port as shown in

Fig.3, which is a snapshot taken above the prototype, you can see the bubble induced flow pushes the oil to the center of the skimmer.

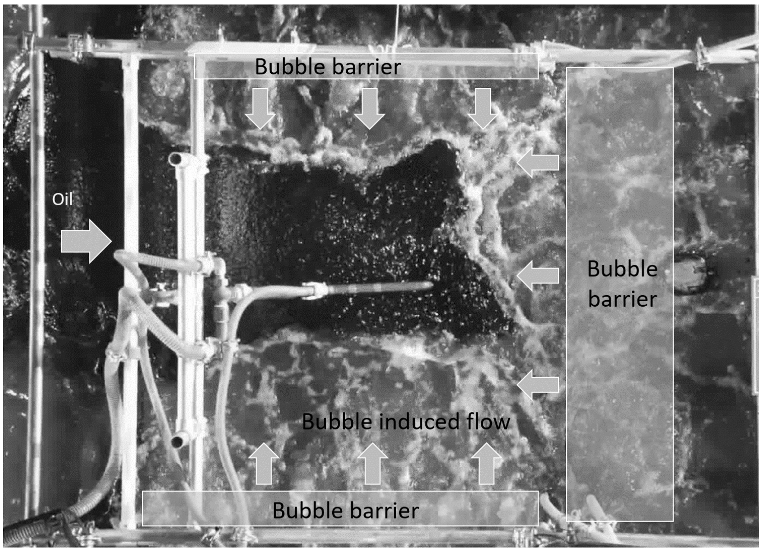


Figure 3 Oil containment by an U-shape bubble barrier

The new oil skimmer uses a water jet ejector for oil suction. As Fig.4 shows, the characteristic point is that it has an L-shape and the suction port faces downstream. The entire unit has a degree of freedom of rotation around a horizontal axis, and a float attached to a rod extending in the downstream direction is designed to keep the suction port at the water surface even in waves. By adopting such a structure, the suction unit does not bow down into the water even when towing at high speed, and water flow resistance can be kept low. When using a water jet ejector, the flow in the recovery pipe has much water content and is stored in the recovery tank. The excess free water in the recovery tank is recycled to the high pressure pump or discharged overboard.

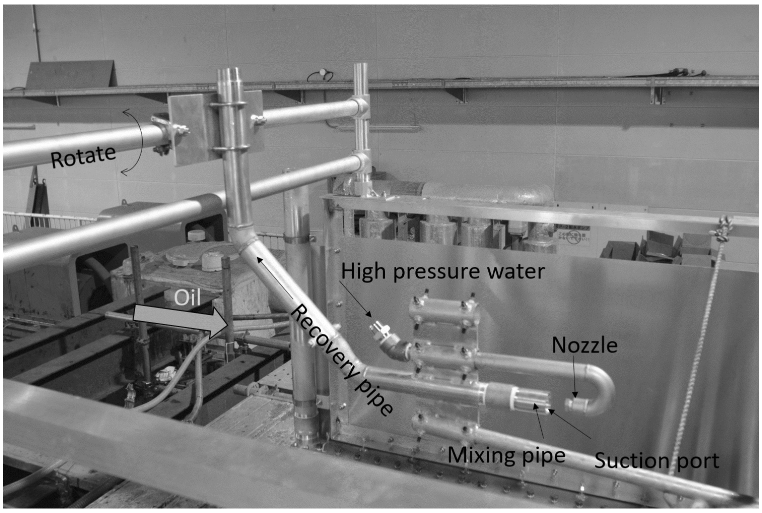


Figure 4 Ejector suction unit

Major specifications of the latest prototype are summarized in Table 1.

Table 1 Prototype model specification

Item	Description
Overall	• Dimension:1945x1708x1000(LxWxH) • Material:Aluminum • Weight:195kg
Bubble barrier	• Structure-integrated • Sides : 1 line(1345mm), diffuser holes : 15 • Stern : 4 line(1480mm), diffuser holes : 18 • Diffuser hole diameter : 3 or 6 • Air Compressor: 11.0m^3/min, 0.7MPa
Suction device	• Pipe: 40A to 50A, Aluminum • Ejector: ○ Nozzle diameter : 5mm ○ Mixing tube diameter: 25-40mm • Pump: ○ Type : Plunger pump (Arimitsu MP-1605) ○ Motor : 11kW 4P 200V induction motor ○ Max. pressure : ~4.9MPa

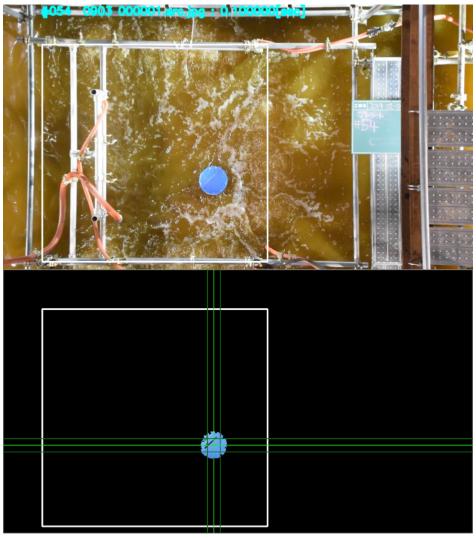
3. Experimental

3.1. Overview

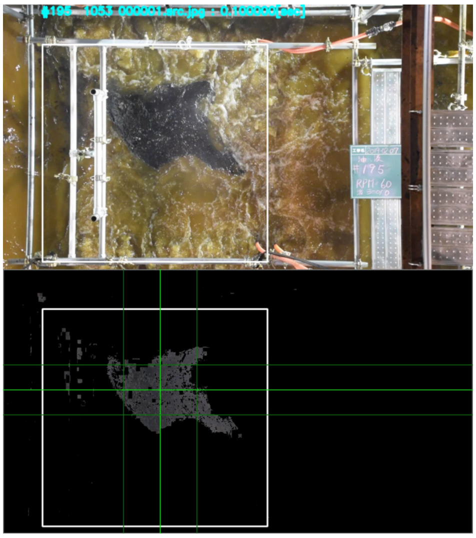
The prototypes test were conducted in a large scale test tank named STORMS(I.Fujita,2008), which can simulate water current and wave. The prototypes described in the previous chapter were installed in the STORMS to be tested under various water current conditions as well as wave. The tests include evaluation of oil containment by the bubble barrier, oil recovery performance as an evaluation of the entire system, and evaluation of the individual mechanical elements that make up the system. In particular, the author focused on the questions of whether bubble barriers, which do not use solid elements as in conventional oil skimmers, can retain oil in the water current, and also whether ejector-type oil suction can efficiently recover oil from the water surface. High-viscosity W/O emulsified C-heavy oil, whose viscosity was nearly 112,000 cP, was used for the tests. The evaluation methods included the measurement of physical quantities such as mass, pressure, and flow rate, as well as image processing analysis using video images.

3.2. Bubble barrier evaluation using image processing

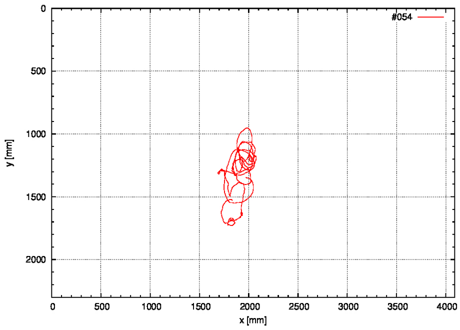
To evaluate the oil containment performance by the bubble barrier, the author employed video processing techniques. As a target for image processing, a cylindrical float and actual oil were used. In the experiment, the movement of the float or oil on the water surface surrounded by the bubble barrier on three sides was video-recorded by a camera installed above the test tank. The recorded video data was converted to still images, and the targets of interest were extracted by image processing on each image. The target extraction was performed by specifying the range in HSV color space using OpenCV. Samples of the image analysis are shown in Fig.5. The image on the left is from the float test, and the image on the right is from the actual oil test. The middle images show the result of the image analysis which give the thick green lines as the center of gravity, and the thin green lines as the spread of standard deviation. The bottom plots give the movement of the gravity center in x-y plane.



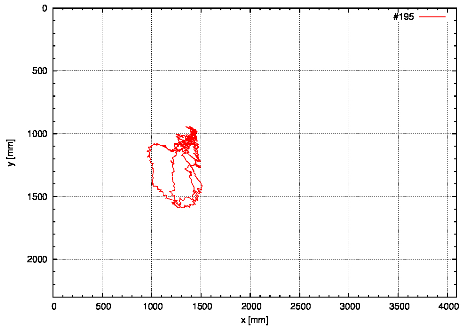
video processing
(Click to see movie)



video processing
(Click to see movie)



Movement of the gravity center
(a)Float test



Movement of the gravity center
(b) Oil test

Figure 5 Observation of containment by bubble curtain

3.3. Water Suction Test

In order to develop the new skimmer successfully, it was necessary to understand the suction performance of the ejector alone prior to the performance evaluation of the entire system. For the evaluation of the ejector alone, suction experiments were conducted with water as the suction target with the cross-sectional area ratio of the nozzle and mixing tube as the structural parameter. The diameter of the water jet nozzle was fixed at 5.4 mm and set at a distance of about 10 mm from the end of the mixing tube, as shown in Fig.7(a). Four types of mixing tubes with diameters of 20, 25, 30, and 35 mm were prepared, as shown in Fig.7(b). Measurements were taken by placing the device on the test water surface and suctioning only water with no oil. Experimental setup is shown in Fig.6.

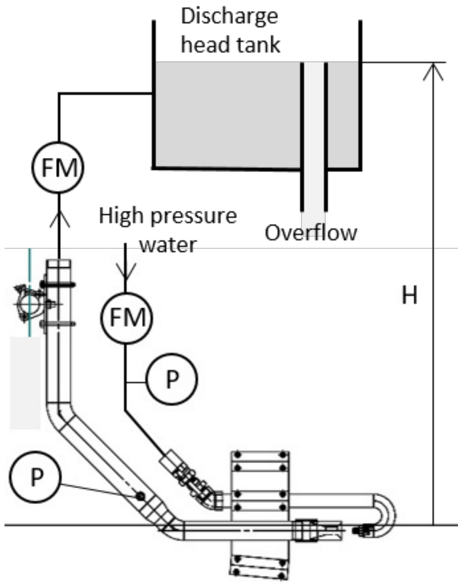


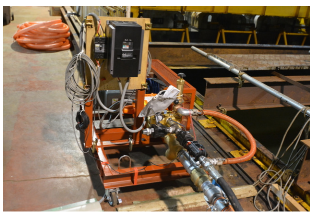
Figure 6 Schematic of water suction test

The head from the test water surface to the collection tank was set at 2.5 m. The flow rate of the drive water was measured using a clamp type ultrasonic flow meter (Keyence FD-Q) due to the large line pressure, and the discharge flow rate was measured using an electromagnetic flow meter. For better understanding, pictures of the major components used in the test are shown in Fig.8

(a) Ejector configuration

(b) Mixing tubes

Figure 7 Ejector configuration and mixing tubes



(a) Plunger pump unit

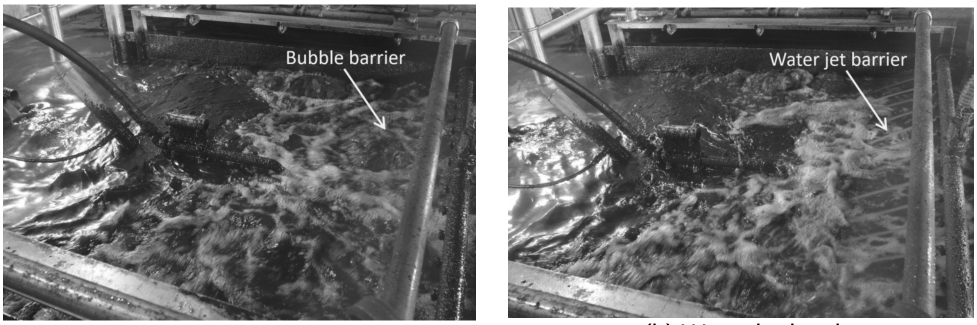
(b) Ejector unit on the water surface

(c) Recovery tank unit

Figure 8 Components for ejector suction test

3.4. Oil Recovery Test

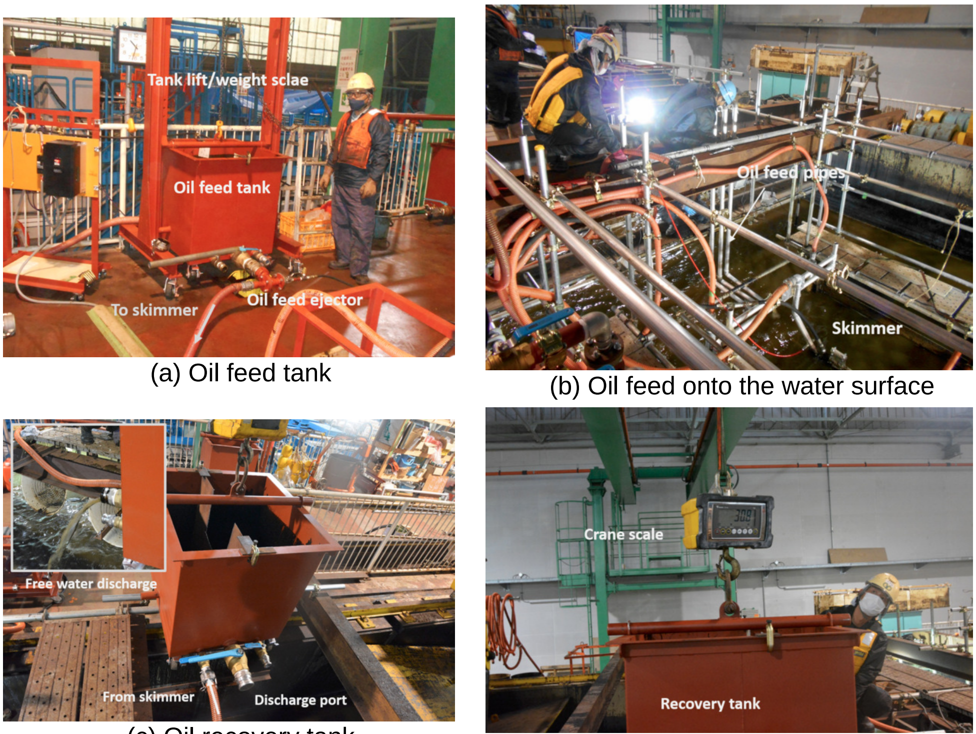
In this section, the method of performance evaluation experiments for oil recovery of the prototype skimmer which combines the ejector device and the bubble barrier is described. The key to this developmental study is the use of bubble barriers to dam the oil to a certain area in the flow without the use of solid elements, but other methods are possible. One method that has already been put to practical use is water cannons barrier (I.Fujita,2013), which is a high pressure water jet shot upstream with a small angle to push back oil on the water surface. For comparison, in addition to the bubble barrier shown in Fig.9(a), oil recovery experiments were also conducted when using a water cannon barrier as shown in Fig.9(b).



(a) Bubble barrier (b) Water jet barrier

Figure 9 Hydrodynamic oil containment

In the test, actual heavy oil was spread on the water surface and collected by the prototype machine. A fixed amount of oil was fed upstream of the model from the oil supply tank by an ejector device, and the oil was collected until the sprayed oil was visually removed from the water surface. The recovered oil and water were temporarily stored in a recovery tank, and after decanting the free water, the recovered weight of only the oil without water was measured. Major items used in the experiment are shown in Fig.10. During the experiment, depending on the water current velocity, the flow rate of the air supplied to the bubble curtain was manually adjusted so that the oil would collect at the suction port for the most efficient oil collection. The evaluation was based on the ratio of oil collected to the amount of oil spread.



(a) Oil feed tank (b) Oil feed onto the water surface

(c) Oil recovery tank (d) Weight measurement

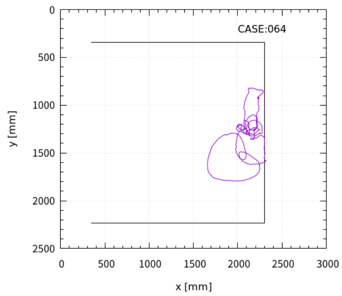
Figure 10 Oil recovery test procedure

4. Result and Discussions

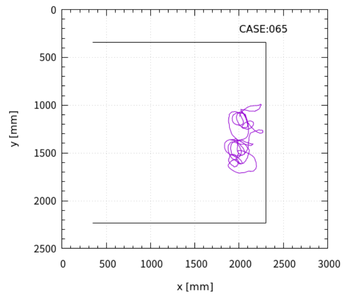
4.1. Oil containment by bubble barrier

This section provides experimental results and discussion of oil containment by bubble barriers. To understand the basic characteristics of bubble barriers, the results of the experiment using floats is given firstly. An example of the results of image analysis of the float position when the towing speed (the water current velocity), U_T, is 17.0 cm/s are given in Fig.11. The figure shows the motion trajectory of the float for about 100 seconds. P_a is the pressure of the air supplied to the air diffusion pipe installed downstream. In this experiment, the air flow rate was not measured directly, but the pressure gives an indication of the air flow rate. According to the nozzle theory, when the pressure is below a certain critical value, which is about 0.072 MPa for this study, the air flow released from the air diffusion pipe is subcritical. In this case, the air flow rate is proportional to the square root of the pressure. On the other case when the pressure is larger than the critical value, the air flow becomes critical when it passes through the diffuser hole becomes critical and has its flow rate be in proportion to the pressure.

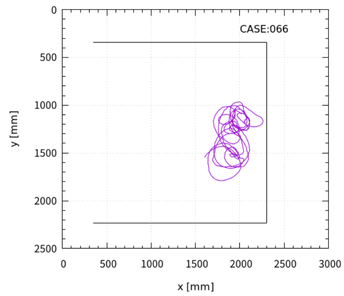
In the case of a conventional oil boom, oil accumulates at the apex of the parabolic shape, however in the case of the bubble barrier, the location of accumulation can be actively controlled, which is one of the most distinctive features. The motions of the center of gravity of the floats are given in Fig.11. The figure shows that the floats are kept inside the U-shape area surrounded by the bubble barrier, and also its mean X position shifts upstream as the air flow rate increases. Moreover, the range in which the float moves around can be evaluated by the standard deviation of the trajectory, and as shown in Fig.12 , it can be seen that the range is narrowed down considerably in both the X and Y directions. In the prototype configuration, bubble lines were placed on the both sides in addition to the downstream side, so that concentration takes place not only in the x-direction but also in the y-direction.



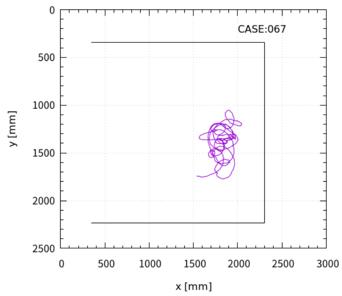
(a) $P_a = 0.025$ MPa



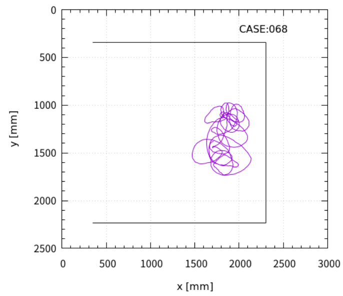
(b) $P_a = 0.030$ MPa



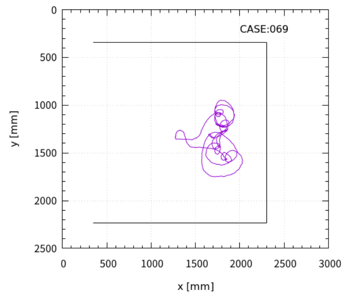
(c) $P_a = 0.035$ MPa



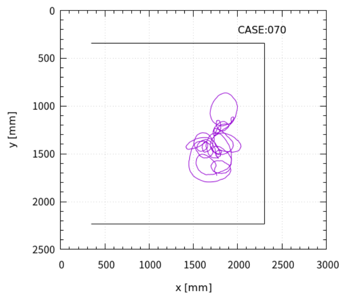
(d) $P_a = 0.040$ MPa



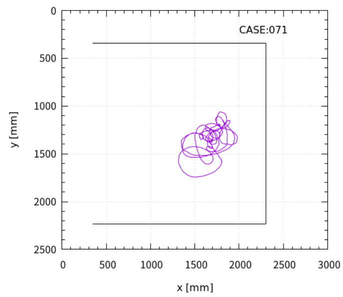
(e) $P_a = 0.045$ MPa



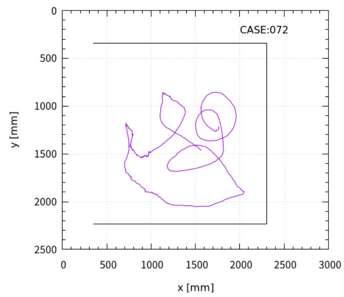
(f) $P_a = 0.050$ MPa



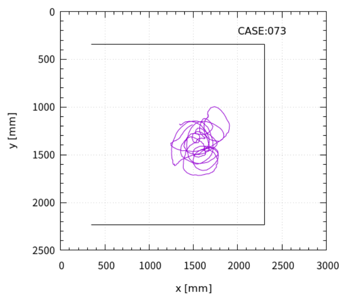
(g) $P_a = 0.055$ MPa



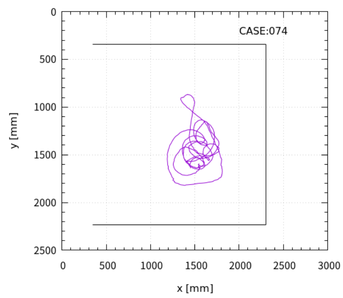
(h) $P_a = 0.060$ MPa



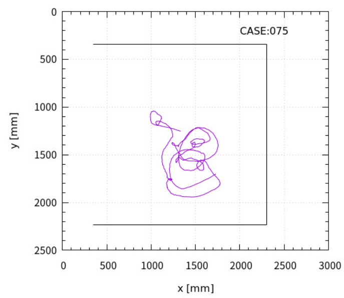
(j) $P_a = 0.065$ MPa



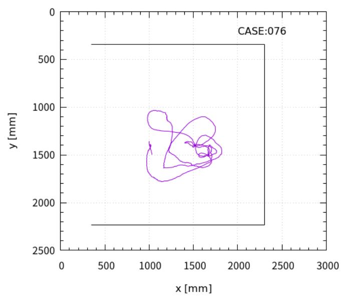
(k) $P_a = 0.070$ MPa



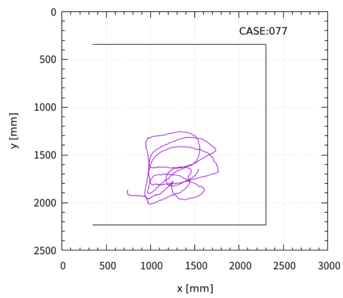
(l) $P_a = 0.075$ MPa



(m) $P_a = 0.080$ MPa



(n) $P_a = 0.085$ MPa



(o) $P_a = 0.100$ MPa

Figure 11 Trajectories of float
($U_T = 17.0$ cm/s)

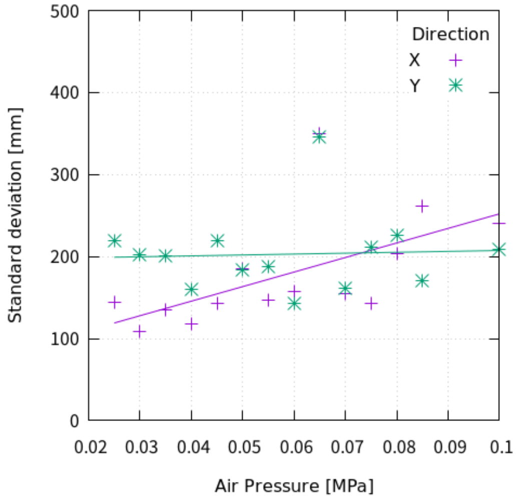
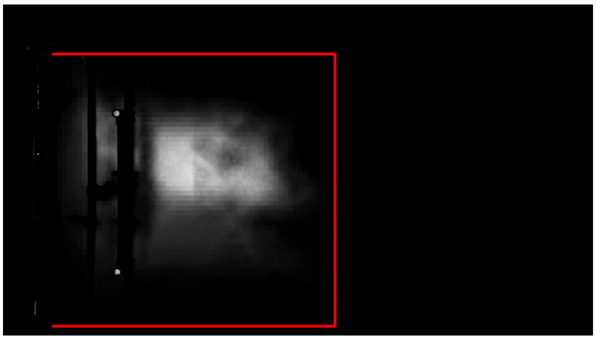


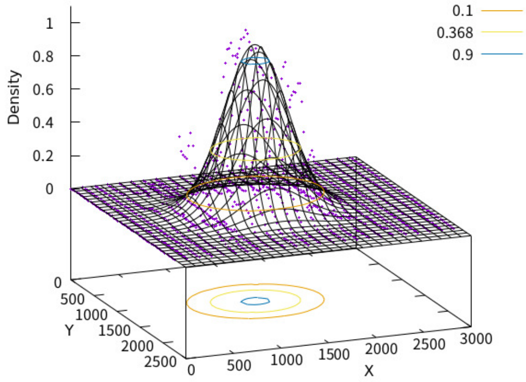
Figure 12 Standard deviation of float center

The concentration by the bubble barrier was also observed when oil is used instead of float. Figure 13 gives its example. The white cloud pictures shown on the left side of the figure are superimposition of each frame of the oil extraction movie, and those on the right side show the probability density distribution of the oil, obtained by quantifying the image data on the left. The distribution ψ is assumed to have a 2-D normal distribution as follows:

$$\psi(x,y) = Cexp\left\{-\frac{(x-x_0)^2}{2{\sigma_x}^2}\right\} exp\left\{-\frac{(y-y_0)^2}{2{\sigma_y}^2}\right\} \quad (1)$$

The upper row (a) shows the results for the water surface without waves, and the lower row (b) shows the results for the water surface with waves. In both cases, the oil gathers into a small area and accumulates there. The effect of waves on the accumulation is small. Since the accumulated oil increases in thickness, it also has the effect of improving the oil-water ratio in suction by the ejector.



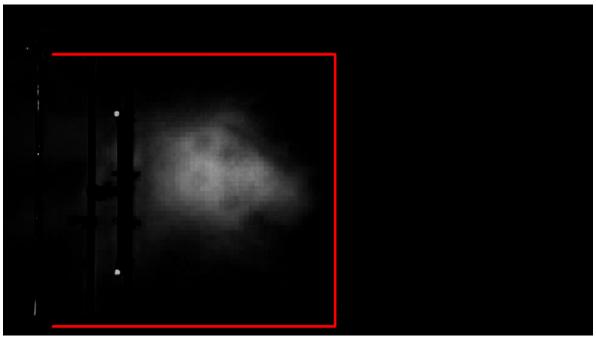


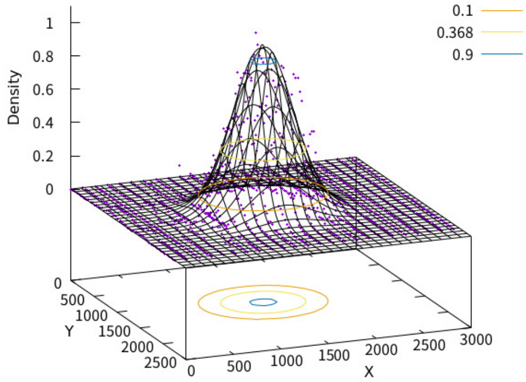
$\sigma_x = 318mm, \sigma_y = 228mm,$

Cumulative image

Density distribution

(a) Without wave





$\sigma_x = 299mm, \sigma_y = 224mm,$

Cumulative image

Density distribution

(b) With wave (Wave height=222mm, wave period=2.5sec)

Figure 13 Oil contaiment by bubble barrier
($U_T = 20.4$ cm/s)

The position of the oil accumulation can be controlled Figure 14 gives its example. Even if the towing speed changes, the position of the float can be brought to the desired location by adjusting the air supply correspondingly. These results are from a float test, but the same control is possible with oil. Actually in the oil recovery test described below, the air flow rate to the bubble barrier was adaptively adjusted so that the oil would be concentrated at the suction port of the ejector.

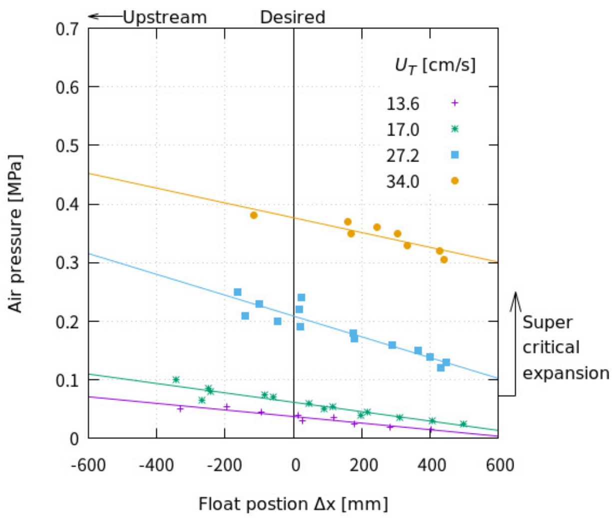


Figure 14 Adaptive control of oil position by bubble barrier

4.2. Ejector suction test

In this development, a water jet ejector was newly designed as a suction device to recover the oil from the water surface. This section provides the experimental results of the stand-alone ejector test conducted prior to the comprehensive testing of the prototype oil skimmer , and compares them to a theoretical ejector model. An ejector is essentially a device that distributes the momentum of the driving fluid, a high-speed fluid, into the momentum and pressure rise of the fluid to be suctioned, and its basic properties can be understood from the conservation law of momentum. While the detailed derivation of the equation is given in the appendix, the simplified conservation law of momentum in the ejector written in dimensionless form is as follows:

$$1 = \frac{1}{\alpha}(1 + \frac{Q_s}{Q_j})^2 + \frac{1}{2}\alpha\frac{P_d - P_s}{P_j - P_s} + \frac{1}{2}\alpha\frac{P_{loss}}{P_j - P_s} \quad (2)$$

, where α is the ratio of the area of the mixing tube and to the area of the jet ($= \frac{S_m}{S_j}$), Q_j and Q_s are volume flow rates of jet and suction, respectively, P_j,P_d,P_s and P_{loss} are pressures of the jet, discharge outlet, suction inlet and loss, respectively. This equation is normalized by the momentum of the jet entering to the ejector which is $\rho\frac{{Q_j}^2}{S_j}$, thus the left-hand term takes unit value. On the other hand, each term in the right-hand side has the following physical meaning. The first term is the flow term which represents the momentum leaving the ejector. The second term represents the increase in head, and the third term represents the loss in the ejector. The only structural parameter in Eq.(2) is α, which changes the characteristics of the ejector. In this test, the nozzle diameter of the jet was kept constant at 5.4 mm, and the diameter of the mixing tube was varied in the range of 20 to 35 mm.

The test was conducted in the form of an ejector placed at the water surface and pumping water into an discharge head tank with a water head of 2.5m. Figure 15 gives the relationship between flow rate and pressure in the discharge system obtained by the experiment. The discharge pressure is the sum of the static hydraulic head and the friction loss associated with the flow in the pipe.

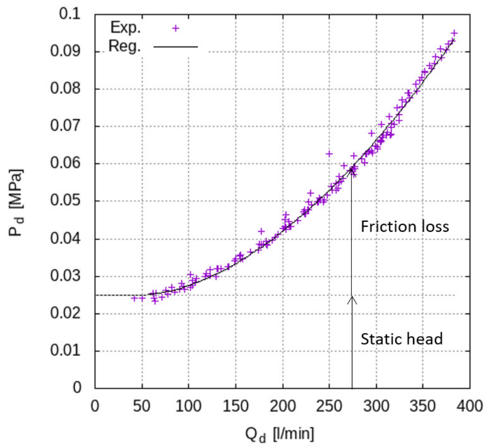


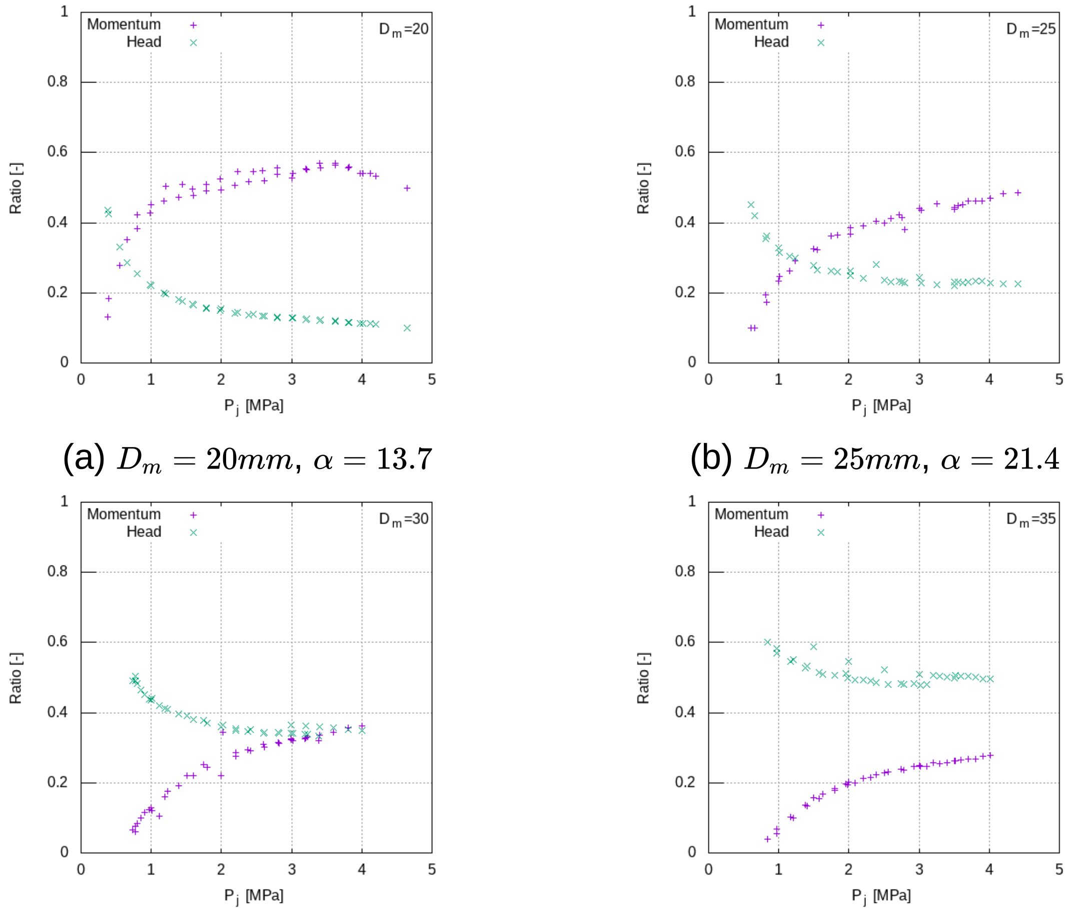
Figure 15 Pressure loss characteristic in pipeline (discharge system)

The regression line in the figure is given as follows:

$$P_{fric} = \lambda {Q_d}^2 \quad (3)$$

,where λ is assumed to be proportional to ${Q_d}^{-1/4}$ according to the well-known Blasius formula (Blasius,1913)for the turbulent flow having the Reynolds number less than 1.5×10^5. As the figure shows, the regression line is in good agreement with the experimental measurements.

The experimental results for momentum distribution are shown in Fig.16. In the case of a small diameter mixing pipe, i.e., when α is small, most of the incoming momentum is spent on the momentum term, while in the case of a large diameter pipe, more is spent on the head term. Considering that ejectors with small α are basically designed for high head and small flow rate, while those with large α are designed for low head and large flow rate, Fig.16 may seem to be contradictory at first glance, but the results are reasonable if we consider the following. When α is small, as in (a), it is structurally easier to achieve high head, so more of the incoming momentum is spent on increasing the flow rate, not on the head. To the contrary, when α is large, as in (d), it is structurally of the high flow type, so that the inflow momentum is consumed in generating the required head.



(a) $D_m = 20mm$, $\alpha = 13.7$

(b) $D_m = 25mm$, $\alpha = 21.4$

(c) $D_m = 30mm$, $\alpha = 30.8$

(d) $D_m = 35mm$, $\alpha = 42.0$

Figure 16 Experimental results of water-jet ejector
Momentum distribution to flow and head
($D_j = 5.4mm$)

Next, we would like to focus on the loss term. Generally, as hydraulics teaches that pressure drop occurs at the inlet from the tank to the pipeline, a similar pressure drop will occur in the ejector. Figure 17 gives the experimental results on the pressure loss, P_{loss}, which defined in Eq.(2). From the figure, it can be observed that the pressure loss is nearly proportional to the pressure, i.e. the square of the velocity, of the incoming jet, and depends on α, and is getting smaller as α is getting larger.

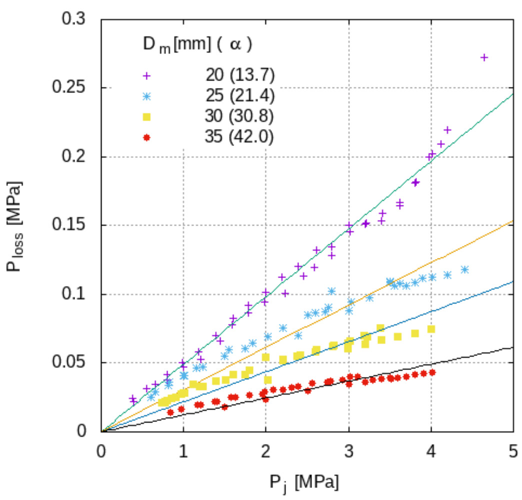


Figure 17 Experimental results of water-jet ejector
Loss term
($D_j = 5.4mm$)

Taking into account the experimental results, and following the general model form of the pressure drop at the entrance of the pipeline, a pressure loss factor ζ is introduced as follows:

$$\zeta=\zeta\left(\alpha\right)=\frac{P_{loss}}{\frac{1}{2}\rho V_j^2} \tag{4}$$

, where it is remarkable that the velocity of the jet is used for the denominator instead the average velocity in the mixing pipe, The factor ζ is assumed to be a function of α which approaches zero asymptotically when α is getting infinity as follows:

$$\zeta\left(\alpha\right)=Cexp\left(-\frac{\alpha}{\alpha_0}\right) \tag{5}$$

Applying this model, as shown in Fig.18, it can be seen that the model can represents the experimental results well.

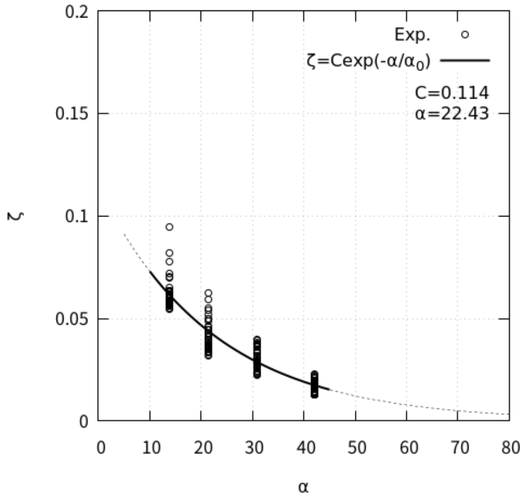


Figure 18 Relation between loss factor and α

A comparison of the experimental results and theoretical prediction for the suction flow rate by the ejector is given in Fig.19, which shows a good agreement between experiment and theory, confirming the validity of the theoretical equation.

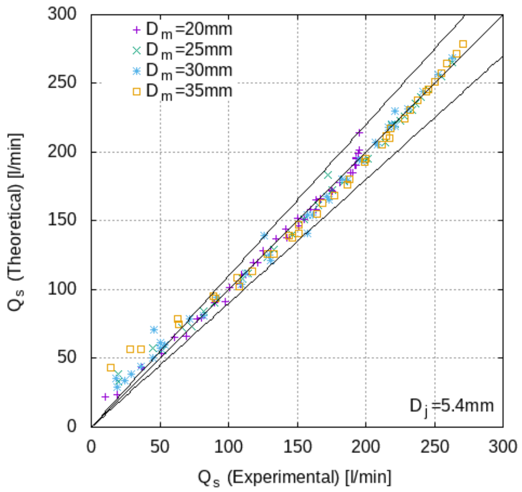
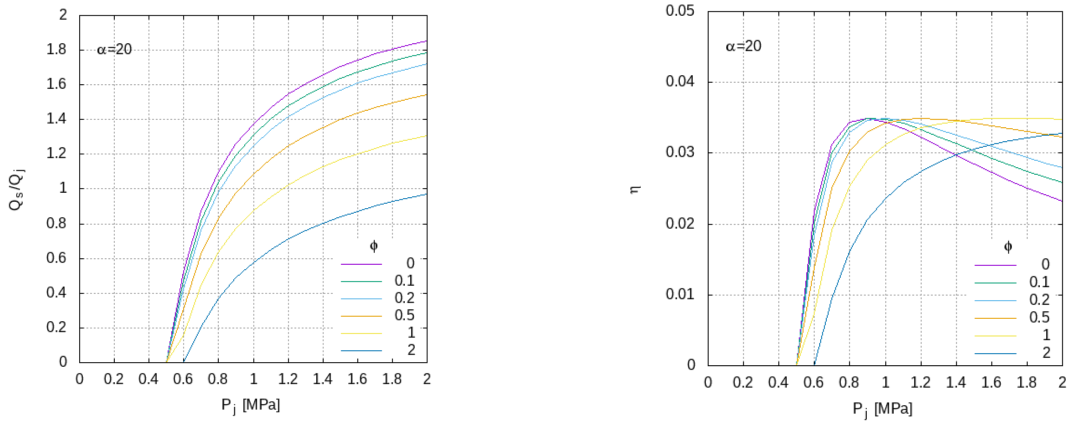


Figure 19 Suction flow comparison between theory and experiment

In the theoretical model given in Eq.(2), the only structural parameter of the ejector is α, which is the ratio of the cross-sectional area of the nozzle and the mixing tube. The most important issue in ejector design is what value to set for α to achieve the desired performance. The optimum value of α depends largely on the system configuration and should be considered for each system. In particular, the effect of the pressure drop characteristics of the discharge system, as seen in Fig.15 , is significant, so we would like to look at that effect here. An example is given in Fig.20 ,which shows the suction performance of an ejector when its α is 20 and the friction loss in the discharge system changes. The parameter ϕ is a hypothetical factor multiplied on λ observed in Fig.15, which changes from 0.001 to 2 here for instance. In Fig.20, the left side shows the suction rate, and the right side shows the efficiency η defined by the following equation:

$$\eta=\frac{Q_s(P_d-P_s)}{Q_j(P_j-P_s)} \tag{6}$$

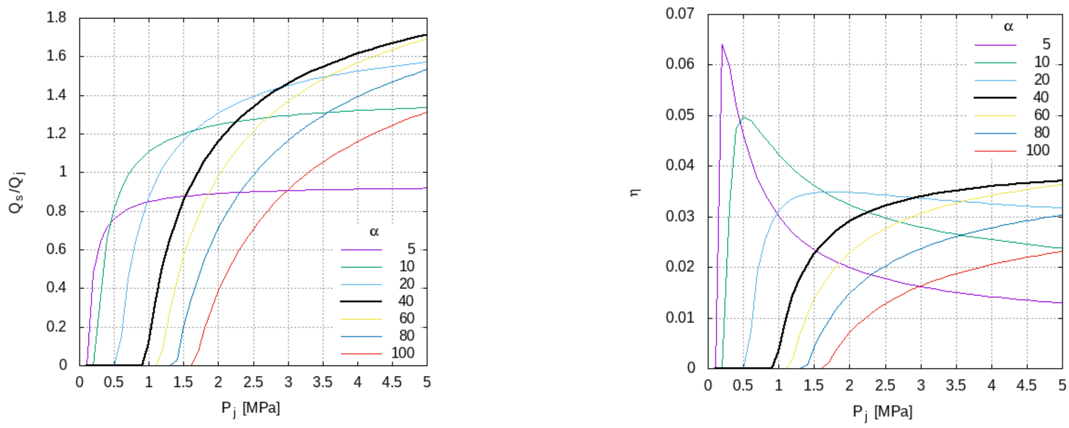
As shown in (a) of the figure, the ratio of suction water volume to jet water volume increases as the jet water pressure is increased, but its rate slows down as the jet water pressure increases. From the viewpoint of work conversion efficiency, it has a peak value at a certain P_j and decreases when P_j exceeds this point as shown in (b) of the figure. In the actual system, α must be carefully determined so that a large suction volume and a high efficiency can be achieved, taking into account the pressure drop characteristics of the discharge system in the pressure range of the jet water allowed to be used.



(a) Suction rate (b) Efficiency

Figure 20 Example of ejector suction performance dependency on friction loss in the discharge system

At the end of this section, the evaluation of the ejector design for the prototype in this study is given. Figure 21 shows the theoretical calculation of ejector performance when using the pressure drop in the discharge system measured in Fig.15. Since the jet water pressure used in this test was planned to be 3.5 to 4 MPa, the figure tells that the α should be around 40 to achieve large suction and high efficiency simultaneously. In the oil recovery test described in the next section, a mixing tube with a diameter of 35 mm was used. Its α was 42.0, which means that this choice is close to the optimal one.



(a) Suction rate (b) Efficiency

Figure 21 Theoretical ejector suction performance (Eq.(2))

4.3. Oil recovery performance

This section provides the results and discussion on the prototype oil recovery performance experiments, whose test procedure was given in Sec.3.4. First, we discuss the air flow rate required for oil containment. In order to recover the oil efficiently, the air flow rate supplied to the bubble barrier must be adjusted depending on the towing speed, so as to let the oil gather near the suction port of the ejector. In particular, downstream bubble barriers are greatly affected by velocity, as they need to push back the incoming flow. The air flow rate of the downstream bubble barrier in the oil recovery experiment is shown in Fig.22. The figure includes the experiment using the current prototype as well as the experiment using a primitive prototype conducted in the previous year. A regression line in the figure is assumed to be (I.Fujita,2016):

$$U_T = \zeta \left(\frac{g Q_a}{L} \right)^{1/3} \tag{7}$$

, and is in good agreement with the experimental results.

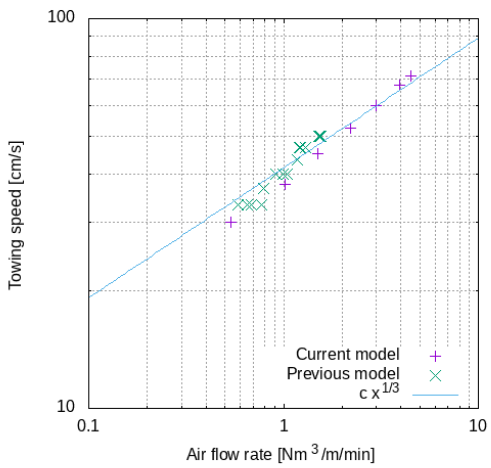


Figure 22 Air flow rate to bubble barrier (downstream)

Next, we discuss the oil recovery performance. As is generally the case with oil fences, when the towing speed increases, Kelvin-Helmholtz instability occurs, and the oil on the surface of the water dives into the water and escapes downstream. Therefore, one of the important index to determine the oil recovery performance is how much of the oil that the skimmer encounter can be recovered, which is called "oil recovery ratio", ϕ, whose definition is as:

$$\phi = \frac{[\text{Recovered oil}]}{[\text{Incoming oil}]} \tag{8}$$

The measurement results for the oil recovery ratio are shown in Fig.23. The X-axis is the towing speed and the Y-axis is the oil recovery rate. The lines in the figure are regression using a following function:

$$\phi(U_T) = \frac{1}{2} erfc(U_T - U_0) \tag{9}$$

The figure shows the results with the bubble barrier and with the water jet, and also includes an existing oil skimmer with a steel boom shown in Fig.24 for reference (I.Fujita,2008). The common feature of the three methods is that the recovery ratio has a high value close to 1.0 when the towing speed is small, it, however, tends to decrease as the towing speed increases. This can be explained by the oil leaking into the water due to the instability caused by the increased shear rate, as mentioned earlier.

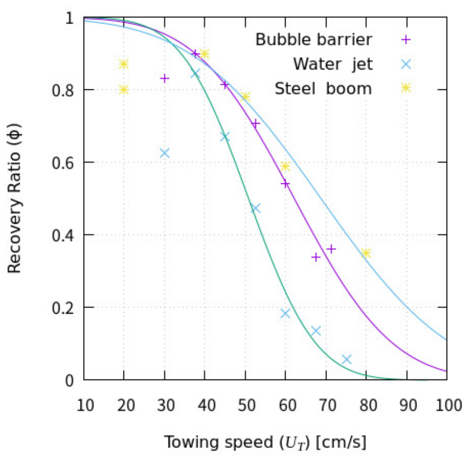


Figure 23 Oil recovery ratio

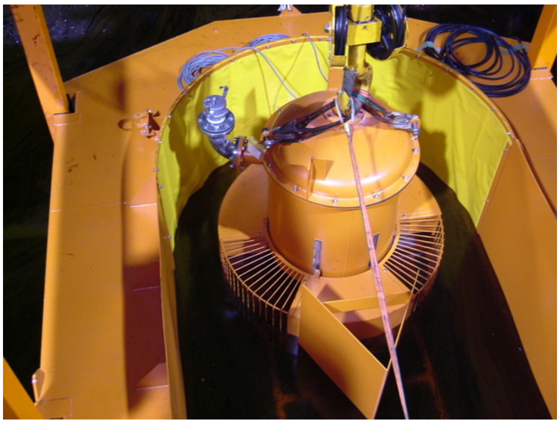
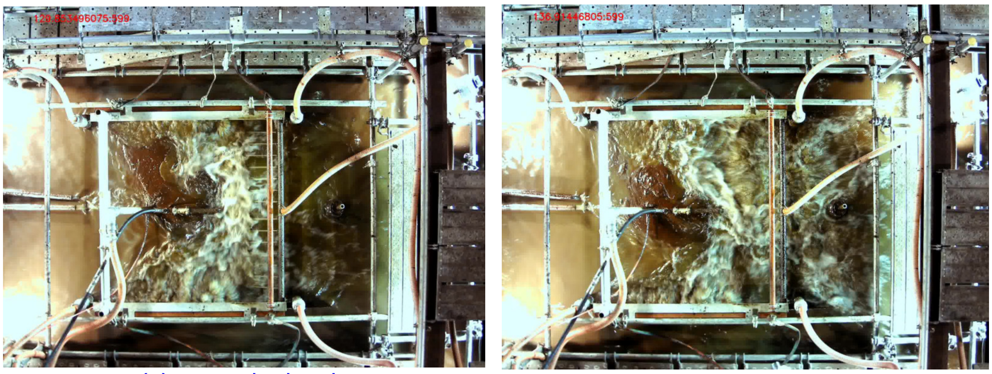


Figure 24 Steel boom oil skimmer

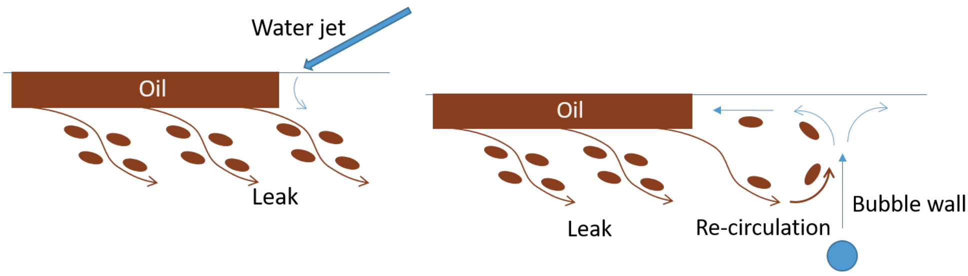
The difference between the methods can be seen in the degree of decrease. The bubble barrier method and the water jet method are compared. In visual observation, as shown in Fig.25, the movement of the oil on the water surface did not show much difference, however, there was a significant difference in the oil recovery rate. Both of these methods have in common that they stop the velocity of the water surface, however, there is a difference in what happens under the water. As shown in Fig. 3, the water jet blocks only the water surface and let the oil that leaks into the water escape downstream freely, while in the case of the bubble barrier, the wall of bubbles in the water captures the oil that once leaked into the water and recirculates it back to the water surface. Similar recirculation is expected to occur with solid booms, and in fact, the example in Fig.23 with the steel boom showed a higher recovery rate than the bubble barrier. However, the example of the steel boom oil skimmer is based on an actual full-scale machine, and the draft of the oil blocking plate is 1000 mm, which is larger than the 680 mm draft of the bubble barrier. From a recirculation point of view, it is clear that a larger draft is more advantageous, and taking this into account, a solid boom is not necessarily superior. Rather, the major weakness of the solid boom is that it generates extremely large water flow resistance as the towing speed increases. The bubble barrier is a good alternative method which realize both of low water flow resistance and excellent oil recovery performance.



(a) Water jet barrier (b) Bubble barrier

Figure 25 Visual observation of oil containment

(U_T =20cm/s



(a)Water jet barrier (b)Bubble barrier

Figure 26 Oil leak into the water column and re-circulation

Next, we consider the optimal towing speed. The amount of recovery is a multiplication of the chance of oil encounter and the recovery rate. As the towing speed increases, the encounter rate increases in proportion to the towing speed, but the recovery rate decreases, which is a trade-off relationship. The oil recovery efficiency,

η, is defined as the product of the non-dimensional towing speed and the recovery rate as follows:

$$\eta = \phi\left(\frac{U_T}{U_c}\right) \tag{10}$$

where, U_c is the reference velocity, which is set to 50 cm/s in this case. The results are shown in Fig.27. In all cases, the recovery efficiency has a peak value at a certain towing speed as summarized in Table 2 . Solid weirs, like steel booms, have good efficiency, but the water flow resistance is extremely high, which significantly reduces the maneuverability of the ship. The water jet is not a suitable alternative to the steel boom because of its low maximum efficiency and the significant decrease in efficiency when the ship speed increases. On the other hand, the maximum efficiency of the bubble curtain is close to that of the steel boom, and it can maintain a certain level of high efficiency even when the ship speed increases. Considering the fact that the data of the steel boom was obtained under more favorable conditions than the present experiment, and that the present experimental model is a prototype and has not yet been optimized, it can be concluded that the bubble barrier oil skimmer has a great potential to serve as an alternative device to overcome the weaknesses of the conventional skimmer using solid element oil boom.

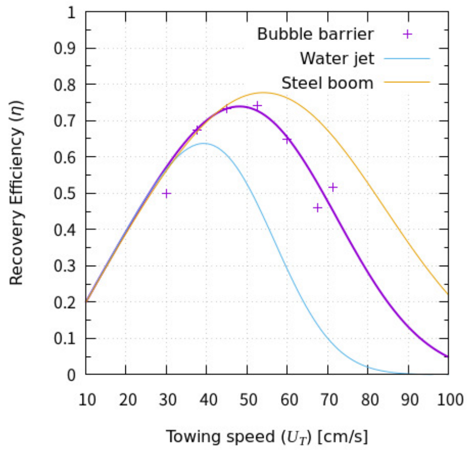


Figure 27 Oil recovery efficiency

Table 2 Maximum oil recovery efficiency

Method	Max. efficiency	Towing speed[cm/s]
Bubble barrier	0.73	48
Water jet	0.63	40
Steel boom	0.77	55

Next, some discussion on the oil-water ratio is given. The oil-water ratio, which is defined as a ratio of oil to the liquid recovered by a skimmer, is one of the indexes to characterize the performance of the skimmer. In the new system, this index is not a major issue because the separation of oil and water is performed in the oil recovery tank, not in the skimmer. However, it can be used as a reference to see how effective the concentration of oil by the bubble barrier is for oil recovery. Table 3 shows an example of the experimental results. Since the oil-water ratio varies greatly depending on the rate of encounter with the oil and the thickness of the oil, the values in the table are not necessarily these values, but data only for comparison. For the water surface conditions, experiments were conducted on a calm water surface with no waves and on a water surface with various wave disturbances. In this test, an oil-water ratio of around 40% was obtained regardless of the water surface conditions, indicating that the oil concentration effect of the bubble barrier was demonstrated. Furthermore, there was no significant difference in the amount of oil collected per unit time between those with and without waves. It is thought that this result was achieved because the mechanism of rotational movement of the suction unit incorporated in this prototype worked effectively to follow the wave motion as shown in Fig.28. It should be noted that the inertia of the rotating part should be as small as possible in order to ensure the wave following performance of such a mechanism. From this point of view, the ejector suction device has a small mass, making it a suitable device for oil recovery equipment.

Table 3 Oil-water ratio

Water Condition	Oil-water Ratio [%]		Oil recovery rate [l/min]	
	Avg	Standard deviation	Avg	Standard deviation
Calm	38.7	12.5	12.53	4.03
Wavy*	41.9	11.8	13.54	3.83

* Includes various wave condition (Wave height:116-222mm, Wave period:1.5-3.5sec)
$U_T = 20.4$cm/sec

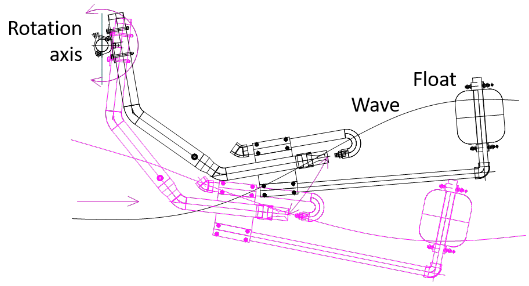


Figure 28 Rotation Mechanism
(Click to see movie)

At the end of this section, the flow in the recovery pipe is described. In the new oil skimmer, the oil is recovered as a mixture of oil and water as shown in Table3 . In this case, the pressure loss in the recovery pipe is not much different from that in the recovery of water alone without oil as shown in Fig.29. The oil used in this experiment had a relatively high viscosity of 112,000 cP, which generally causes extremely high pressure loss if it transferred alone, however, smooth transport in the pipe was achieved by the water jet ejector. The reason why high friction loss does not occur even with high viscosity oil is that the water forms buffer layer between the oil and the pipe wall to prevent the oil to directly contact the pipe wall. Even if the object to be sucked is only high-viscosity oil, it can be transported with small friction loss because the driving water of the ejector serves as a buffer layer. In addition to the mechanical advantages of a simple structure and robustness to debris contamination, ejector suction is also suitable for the collection of high-viscosity oil in terms of flow.

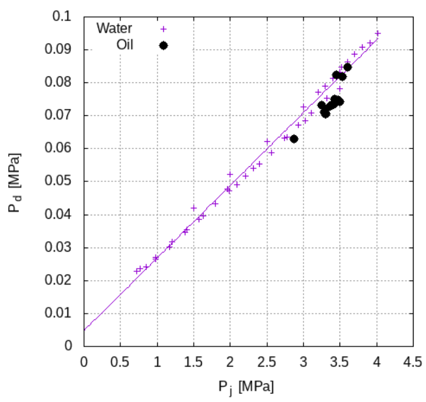


Figure 29 Back pressure at oil recovery test

5. Conclusions

In order to solve the problems of conventional oil skimmers, two fundamental principles were introduced in this study. A new skimmer based on these principles was designed and prototyped. The new skimmer is extremely simple in structure and light in weight, which utilizes bubble barrier to contain oil and water jet ejector as suction device. The prototype model was served to a large scale tank test to evaluate the basic functions, to obtain the following findings:

- Bubble barrier arranged in a U-shape can stop and contain incoming oil as well as concentrate it into a smaller area adaptively.
- Ejector suction experiments were conducted to determine the characteristics, and based on the results, an example of the parameter design of a water suction ejector suitable for oil recovery was presented.
- Ejector suction was proven to be a good option for oil recovery from mechanical structure aspect and hydrodynamic aspect.

- Oil recovery tests were conducted to compare the performance to other methods, and it was found that the combination of bubble barrier and ejector suction could efficiently recover the oil and might be an alternative to resolve the problems that the conventional oil skimmers suffer from.

Acknowledgments

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Appendix - Ejector theory

Nomenclature

Symbols

M : Mass flow rate
P : Pressure
Q : Volume flow rate
S : Cross section area
V : Velocity
ρ : Density

Subscripts

d : of/in discharge
j : of jet or jet nozzle
$loss$: in loss
m : of/in mixing tube
s : of suctioned fluid

The ejector is a classical device and the theory is well established, so it may not be necessary to describe it in detail. Here, however, in order to help the reader understand the main body of this paper, the theory of the water jet ejector with a mixing tube without taper section will be introduced. A schematic of the ejector to be considered is shown in Fig.A-1.

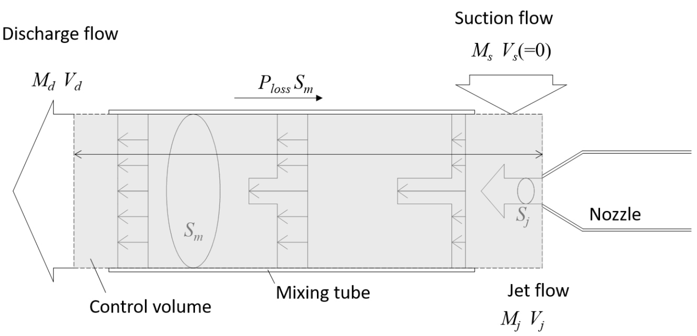

Figure A-1 Theoretical model of water jet ejector

Momentum conservation in the control volume is given by:

$$M_j V_j = M_d V_d + S_m(P_d + P_{loss} - P_s) \quad \text{(A-1)}$$

where, the left-hand side is the momentum of the water jet entering the control volume, and the right-hand side is the sum of the momentum leaving the test volume and the forces acting on the control volume. P_{loss} is the pressure equivalent of the force on the wall of the mixing pipe. Using volumetirc flow rate ($Q = \frac{M}{\rho}$), Eq.(A-1) can be written as:

$$\frac{\rho Q_j^2}{S_j} = \frac{\rho Q_j^2}{S_m}(1 + \frac{Q_s}{Q_j})^2 + S_m(P_d + P_{loss} - P_s) \quad \text{(A-2)}$$

where, the density of the fluid of the jet and the fluid being sucked is assumed to be the same. Bernoulli's principle is applied to the nozzle flow of the water jet, which gives:

$$\rho \frac{Q_j^2}{S_j} = \rho V_j^{\,2} S_j = \rho \frac{2(P_j - P_s)}{\rho} S_j = 2(P_j - P_s) S_j \quad \text{(A-3)}$$

For Eq.(A-2), dividing both sides by $\frac{\rho Q_j^2}{S_j}$ and substituting Eq.(A-3) gives an equation written with non dimensional terms as follows:

$$1 = \frac{1}{\alpha}(1 + \frac{Q_s}{Q_j})^2 + \frac{1}{2}\alpha \frac{P_d + P_{loss} - P_s}{P_j - P_s} \quad \text{(A-4)}$$

where, α is a structure parameter of the ejector defined as $\frac{S_m}{S_j}$. $\frac{Q_s}{Q_j}$ can be explicityly solved, which is:

$$\frac{Q_s}{Q_j} = \sqrt{\alpha - \frac{1}{2}\left\{\frac{P_d + P_{loss} - P_s}{P_j - P_s}\right\}\alpha^2} - 1 \quad \text{(A-5)}$$

Finally, as a reference, the suction characteristics of the ejector for different values of α are shown in Fig.A-2. As can be seen from the figure, the ejector has the basic characteristics so that ejectors with small α have a large discharge head but a small suction volume, while ejectors with large α, on the contrary, have a small head but a large suction volume.

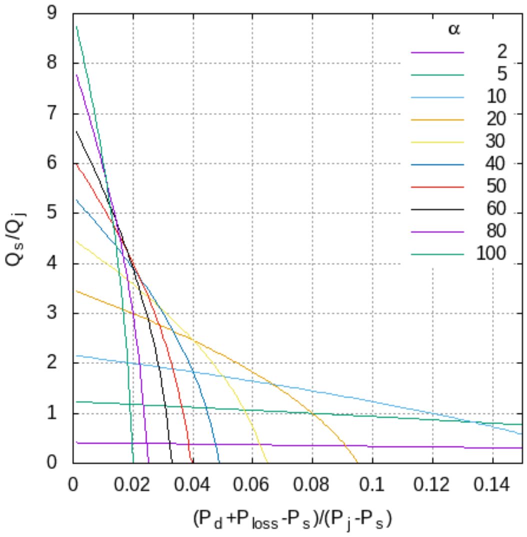

Figure A-2 Theoretical suction performance of water jet ejector