Model experiment on the dynamic process of oil leakage from the double hull tanker

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ABSTRACT

This paper presents an experimental investigation on oil leakage from the double hull tanker (DHT). It is designed to explore the dynamic process of oil leakage from bottom-rupture hole of DHT. The experimental test shows the leakage resistance mechanism of ballast tank space. The behavior of oil leakage from damaged DHT and dynamic features of flow in the overall process are demonstrated from experimental results. The overall process of oil leakage is divided into free-leakage and resistance-leakage stage according to the corresponding power to study the dynamic features of oil-water flow inside or outside the tank. The corresponding dominated factors of oil leakage in different stage are also pointed out, and the unsteady Bernoulli's equation is used to verify experimental results. Meanwhile, viscous effect in leakage process is discussed and the importance of hydrodynamic features associated with the mechanism of oil leakage is explored from experimental results.

KEY WORDS: **Double hull tanker; dynamic process; model experiment; oil leakage; viscous effect**

1. Introduction

Double hull tanker (DHT) design was regulated in 1992 by the International Maritime Organization (IMO) for the purpose of minimizing oil leakage in an event of a casualty (Yamaguchi and Yamanouchi, 1992). It was widely accepted that DHT is the most effective design to reduce oil leakage from a damaged tanker due to collisions and groundings in the past twenty years. So far, many experimental and numerical investigations on DHT in incidental scenarios have been carried out by different researchers. The effect of emulsification on oil leakage from damaged tanker in a series of model tests with different kinds of oil has been explored (Debra et al., 2001, 2003). The model which could determine the process of oil leakage due to changes of gravity and wave pressure caused by movements of vessel or waves on the surface was developed (Fthenakis et al., 2003). Meanwhile, numerical analysis and probabilistic methodology have been used to investigate the behavior of oil leakage. ((Hart and Hancock ,1992; Daidola et al., 1997; Smailys and Mindaugas, 2006). However, oil leakage is clearly a dynamic and unsteady procedure, the explorations on oil leakage from damaged DHT have not been found in literature. The investigations on oil leakage from single hull tanker can be found in only a few papers among the available publications (Tavakoli et al., 2008, 2009, 2010, 2011, 2012). The hydrodynamic features of oil and water flow during this process have been confirmed in these investigations on single hull tanker. The ultimate volume of oil leakage due to accidental groundings or collisions could be provided in these aforementioned explorations. As these explorations were mainly based on the steady or quasi-steady assumption and focused on the ultimate amount of oil outflow or water inflow, the dynamic behaviors and the viscous effect on oil leakage have not been explored. Numerical simulation is the effective tool to capture the hydrodynamic features of oil leakage from oil tankers (Lu et al., 2010; Xiao et al., 2010; Krata et al., 2012), such as the Moving Particle Semi-Implicit method (MPS) (Koshizuka, 1996) as well as the PNU-MPS approach (Lee et al., 2011). The references cited above only focused on the single hull tanker (SHT), and the corresponding numerical studies related to DHT are rarely seen in literature, partially due to the complexity caused by the narrow ballast space in DHT compared with SHT. The oil-water flows from grounded tank of DHT was simulated by the program 'Flow-3D' without considering the viscosity of fluid (Peter and Lin, 1994) and the numerical investigations on oil leakage from grounded or collided cargo tankers with different hull structures (including DHT) was conducted with 2D model (Tavakoli et al., 2008; Lee et al., 2011). Nevertheless, most of the aforementioned investigations were restricted by two-dimensional condition or neglect of viscous effect, which leads to irrational numerical results, especially for flow flux (Cheng et al., 2010).

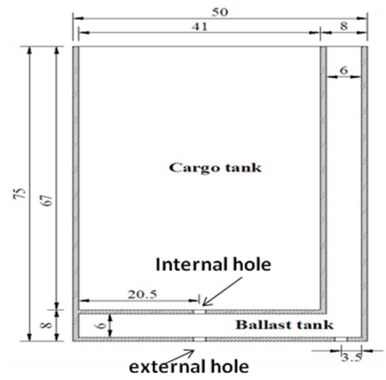
Obviously, in order to predict the behavior of submerged oil leakage and propose optimal designs to reduce the volume of oil leakage to sea, it is necessary to understand leakage resistance mechanism of ballast tank space. Relying on the model experiment, detailed investigation on the dynamic process of oil leakage from DHT was presented by analyzing flow features. Configurations of two broken holes (puncturing through two hulls) located on the bottom of tank (Tavakoli et al., 2010, 2011) were used to reflect the grounding incidents, respectively, and model tank is fixed and initially located in still water basin. The focus of the paper is to explore the factors of oil leakage from cargo tank. The Unsteady Bernoulli's equation is used in predicting volume of oil leakage from cargo tank. Based on the data from model test, the process of oil leakage into basin is presented and the behavior of ballast tank capturing oil from cargo tank is illustrated based on the hydrodynamic features of flows. More importantly, viscosity effect is considered in this exploration.

2. Experimental design

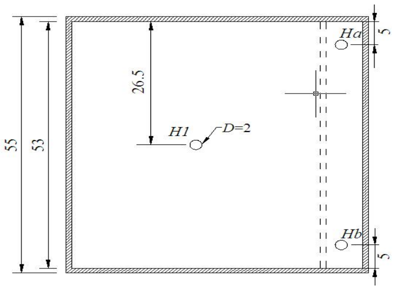
Similarity principles considering both Froude number and Reynolds number are adopted to achieve kinematic and dynamic similarity (Tavakoli et al., 2008). Vegetable oil with density of 915 kg/m^3 and viscosity of 3.2×10^{-5} m^2/s was chosen as the model oil. The density and the kinematic viscosity of water are 998 kg/m^3 and 1.0×10^{-6} m^2/s, respectively.

2.1 The model tank

A model tank was built at 1/40 scale of a typical tank which takes a side section of VLCC ignoring details of internal support structures inside ballast tank (Thomae, 1995; Karafiath,1992). Similar to the previous investigations (Karafiath, 1992), a J-shape ballast tank (sketched in Fig.1 (a)) was used. The height, breadth and the length of the external tank are 0.75m, 0.5m and 0.55m, respectively. The whole model is made of watertight plywood and glass for the purpose of visual observations. The thickness of the glass wall is 1cm. The height of the bottom ballast space and the width of the side ballast space are 0.06m. Two coaxial circular holes with diameter of 0.02m were drilled on internal and external bottom hull, representing the rupture of the tanker (*H1* in Fig. 1(b)). The dimensional error of scale model in this paper is $\pm 2\times10^{-3}$m.



(a) Front view



(b) Top view

Fig. 1 Dimensions of model tank (a) and location of the hole (b) (unit: cm)

2.2 The basin

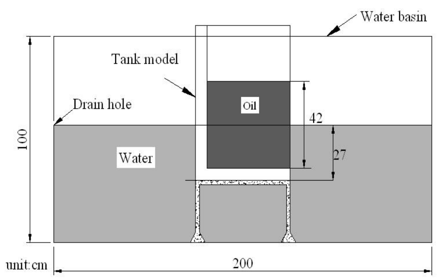
The height, breadth and the length of the external basin are 1m, 1.2m and 2m, respectively. Meanwhile, the drain holes were arranged on the same height of model tank's draft as shown in Fig.2 (a) to ensure a fixed draft of model tank in the process of experiment. The model test was carried out in a controlled environment with temperature of 10±3℃.In the experiments, the hole on the external hull (referred to as external hole) and the hole on the internal hull (referred to as internal hole) were drilled to simulate the puncturing rupture.

The model tank was fixed in a water basin as illustrated in Fig.2 (a).

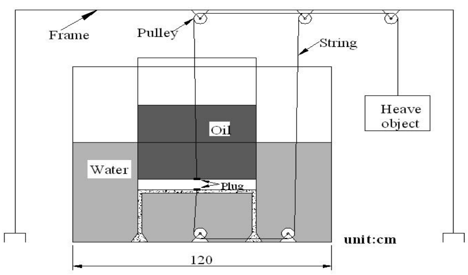
3. Test setup

3.1 Experimental system

Mechanical gates driven by the heavy object were designed and utilized to close/open holes so as to ensure the repeatability of test. As two coaxial circular holes were drilled on internal and external bottom hull, representing the rupture of the tanker, before oil leakage from cargo tank, the coaxial circular holes are plugged by two plugs. In order to avoid the effect of turbulence caused by human factors on whole flow field, fixed pulleys were adopted and arranged in appropriate position of the frame (Fig.2)to make sure that the plugs are pulled out vertically and smoothly.



(a) Front view



(b) Side view

Fig. 2 Sketch of the test system and initial state of model test

Equipments used to observe the leakage phenomenon and measure the data of liquid level or pressure are shown in Fig.3 including computer, sensors, video cameras, meter rulers *et al*.

A meter ruler was fixed vertically on the model tank in order to record height of residual oil in cargo tank. In this test, suitable specifications of sensors (PT210 pressure transmitter and PTP703 level transmitter) were selected according to its sensitivity and resistance to corrosion. Considering the turbulence caused by positions of sensors, the liquid level sensor (PTP703) was installed at the corners of cargo tank as illustrated in Fig.3. And the pressure sensors (PT210) were fixed on the bottom of model tank through reserved holes *Ha* and *Hb* (Fig.1 (b)). Meanwhile, the sensitivity and the accuracy of these sensors have been initially tested to ensure accuracy in order to avoid the effect of sensors on the flow field in the narrow space of ballast tank.

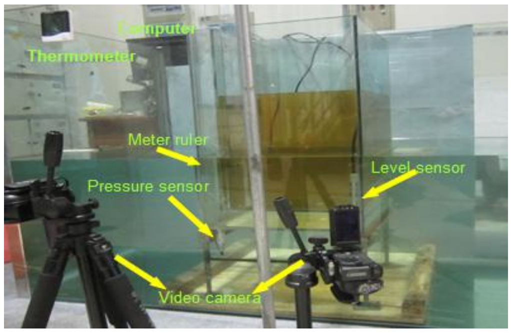


Fig.3 Experimental equipments

3.2 Experimental procedure

Initial height of oil in cargo tank is 0.42m and the draft of model tank is 0.27m. The thickness of the water between model tank and basin bed is 0.3m, representing the narrow space between DHT and seabed in grounding scenario. When the internal hole and external hole were opened simultaneously, oil in the cargo tank and water in the external environment flowed into the ballast tank through internal and external hole respectively. The test data was recorded by sensors in the overall process until the flow of oil and water ceased. The phenomenon of oil leakage from the model tank, particularly oil and water in the ballast tank, was observed by video camera.

4. Results and verification

4.1 Experimental results

The pressure of water-oil mixture in ballast tank is illustrated in Fig.4. Meanwhile, the corresponding time history of height of oil in cargo tank provided by sensor is shown in Fig.5. The height of water-oil mixture in ballast tank is also plotted in Fig.5 through video snapshots in every 0.5

seconds.

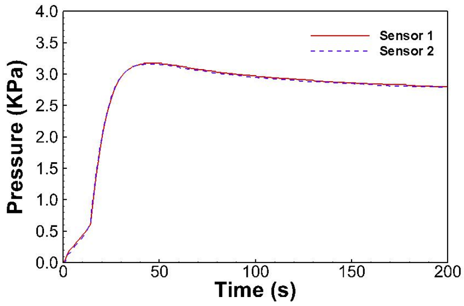


Fig.4 Time histories of Pressure of water-oil mixture in the bottom of ballast tank

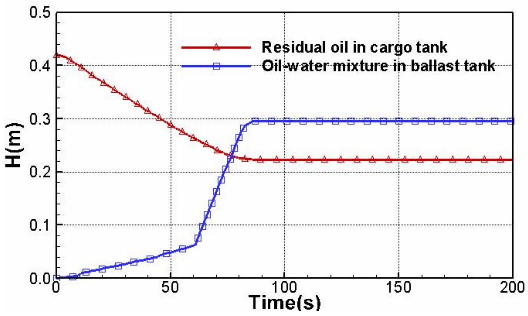


Fig.5 Time histories of height of oil in cargo tank and that of oil-water mixture in ballast tank

Then the volume of oil leakage from cargo tank and that of residual oil in cargo tank can be calculated based on the test data, and the results are presented in the Fig.6.

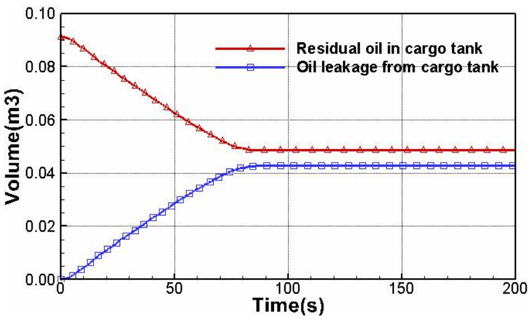


Fig.6 Time histories of volume of residual oil in cargo tank and oil leakage from cargo tank

As shown in Fig.4, the pressure of mixture in ballast tank is almost constant at the end of oil leakage. The range of error about the process of oil leakage is acceptable, which is below 0.5%. But the change trend of pressure of oil-water mixture is obviously different with height of oil-water mixture in ballast tank, and flow characteristics of water and oil in ballast tank are more complicated due to turbulence. Even more importantly, density of oil-water mixture is variable. The exploration on density of oil–water mixture will be carried out by further works.

Considering the time histories of height of oil in cargo tank and that of oil –water mixture in ballast tank(Fig.5), the process of oil leakage can be divided obviously into two stages(free-leakage stage, resistance-leakage stage). In the free-leakage stage, the bottom space of ballast tank was gradually filled with mixture of water and oil. In the resistance-leakage stage, the internal hole was submerged by the oil-water mixture, and the oil-water mixture flows into side space of ballast tank.

The flows of oil and water should cease after the pressure equilibrium was established. But due to larger velocity gradient and shearing stress between oil and water, clear emulsification (water-in-oil and oil-in-water droplets) has been observed, so the measurement of H_{mixture} (the height of oil-water mixture in ballast tank) may have significant error.

4.2 Results verification

When the process of oil leakage ended, assuming a steady state without mixture of the oil and water, the hydrostatic equilibrium in the ultimate stage of model test may be established:

$$\rho_{\mathrm{w}} g H_{\mathrm{b-w}} = \rho_o g H_{\mathrm{d-o}} + \rho_{\mathrm{w}} g H_{\mathrm{w}} \tag{1}$$

$H_{\mathrm{d\text{-}o}}$ is the height of oil in ballast tank， H_{w} is the height of water layer in ballast tank，$H_{\mathrm{b\text{-}w}}$ is the draught of model tank, ρ_o and ρ_w stand for densities of oil and water, respectively. The hydrostatic pressure equilibrium demonstrates the concepts of DHT design, explaining how DHT can prevent oil leakage.

Before oil-water mixture in ballast tank reached bottom of internal hull, the velocity of oil leakage from cargo tank v_{h} can be evaluated by unsteady Bernoulli's equation considering the viscosity head loss：

$$H_{\mathrm{oil}} - \frac{v_{\mathrm{h}}^{2}}{2g} = \alpha \frac{v_{\mathrm{h}}^{2}}{2g} + \frac{L}{g}\frac{dv_{\mathrm{h}}}{dt} \tag{2}$$

Assuming the velocity is uniform along the cross section of the hole and velocity of free surface of the oil in cargo tank is much less than v_h. In Eq. (2), L is the thickness of internal hull and α is the coefficient representing viscous effect; H_{oil} is the height of residual oil in cargo tank. As the thickness of internal hull is small and the velocity of free surface of oil in cargo tank is small, the term of acceleration may be insignificant and the change of v_h is small. Then Eq. (2) can be simplified as follows.

$$H_{oil} - \frac{v_h^2}{2g} = \alpha \frac{v_h^2}{2g} \tag{3}$$

$$v_h = \sqrt{\frac{2gH_{oil}}{1+\alpha}} \tag{4}$$

Once the time history of v_h is determined by Eq. (4), the volume of oil leakage from cargo tank V_{oil} can be determined:

$$V_{oil} = \int_0^t v_h s dt \tag{5}$$

In which, ***s*** is the area of inner hole; ***t*** is the duration of oil leakage, V_{oil} is the volume of oil leakage from cargo tank. And H_{oil} was obtained from experimental result. The flow is complicated when $H_{mixture}$ is more than 6cm. Therefore, the previous Bernoulli's equation may not work due to the effect of pressure head from free surface in water basin and extreme turbulence in ballast tank. However, when H_{oil} and viscous coefficient are determined, it is surprised to find that Eq. (5) can well capture oil outflow from cargo tank in the overall process of oil leakage, whether or not the $H_{mixture}$ is more than 6cm. Fig.7 shows a comparison of the volume of oil in cargo tank measured in experiment and that predicted based on Eq. (5).

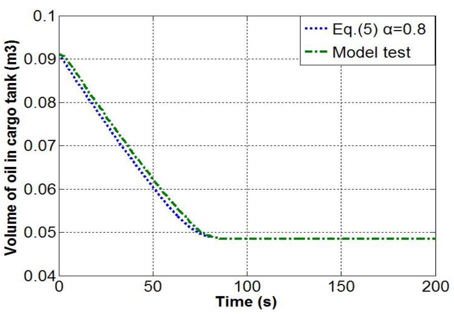


Fig.7 Time histories of the volume of oil in cargo tank

Meanwhile the agreement shown in Fig.7 implies that dominated factor driving oil flow through internal hole may be the difference of hydrostatic head between cargo tank and internal hole, yet the water in basin plays an insignificant role in this particular case.

As shown in Fig.8, Eq. (5) can well capture the oil leakage from cargo tank. Particularly when the viscous coefficient α is 0.8, the accuracy of experimental result is well illustrated. Meanwhile, the viscous coefficient plays a significant role in the process of oil leakage from DHT. Therefore, if only considering non-viscous assumption, the exploration on oil leakage may have significant error.

5. Discussions

As mentioned above, there are two obvious stages in the process of oil leakage. Meanwhile, according to the Bernoulli's equation (Eq.2), H_{oil} is for the stage where $H_{mixture}$ is smaller than 6cm (the free-leakage stage). After $H_{mixture} >$ 6cm(resistance-leakage stage), H_{oil} in Eq. (2) is replaced by height differences between oil surface in cargo tank and surface of oil-water mixture in ballast tank(i.e. $H_{oil}=H_{oil}(t)-H_{mixture}+0.06$, $H_{oil}(t)$ is the height of oil in cargo tank at t s in resistance-leakage stage). Here different flow characteristics are discussed in these typical stages, particularly the features of water and oil in ballast tank.

5.1 Dynamic characteristics of flows in free-leakage stage

When holes were opened simultaneously, the oil in cargo tank and the water in external environment flowed into ballast tank. The potential head difference between internal hole and oil-air interface in cargo tank (0.42m) is larger than that between external hole and air-water interface in water basin (0.27m). So the momentum and velocity of oil leakage from internal hole is significantly higher than that of water from basin. Also, the downward oil flow from internal hole was accelerated while the upward water flow was decelerated by gravity. Therefore, water jet was pushed down by oil jet. Then oil jet prevented water flowing into bottom space of ballast tank, eventually oil leaked into basin. The height of residual oil in cargo tank and the height of oil-water mixture in bottom space of ballast tank are plotted in Fig.8. In this stage, the internal hole was not submerged by the oil-water mixture in ballast tank, and the internal hole was still exposed the air in ballast tank. In the cargo tank, oil only interacted with air in upper space of cargo tank. So the oil leakage from cargo tank was dominated by the height of oil in cargo tank in free-leakage stage. The residual volume of oil in cargo tank decreased sharply, and the volume of oil leakage from cargo tank almost increased linearly as shown in Fig.10.

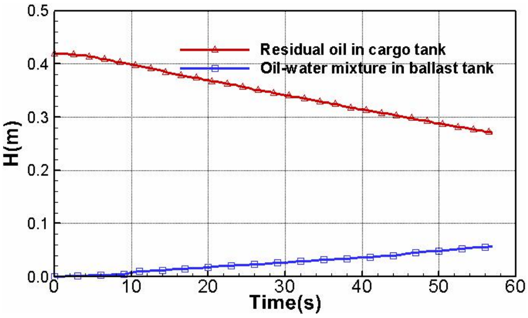


Fig.8 Time histories of height of residual oil in cargo tank(H_{oil}) and that of oil-water mixture in ballast tank ($H_{mixtrue}$) in free-leakage stage

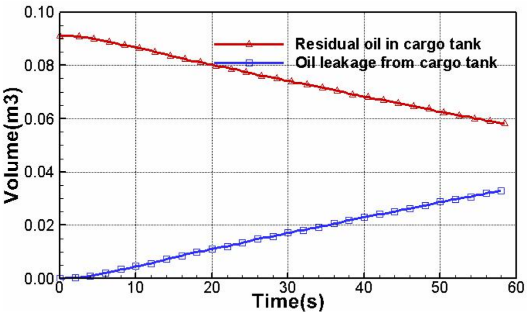


Fig.9 Time histories of volume of oil leakage in cargo tank and residual oil in cargo tank in free-leakage stage

When the oil-water mixture in ballast tank reached the bottom of the internal hull and the internal hole was submerged by oil–water mixture in ballast tank, the free-leakage stage ended.

In free-leakage stage, the typical images of flow features in bottom space of ballast tank were recorded by video camera. After oil leaked into water basin, oil flow extended towards bottom of water basin. Due to larger velocity gradient and shearing stress near on interface between oil and water, clear emulsification, water-in-oil and oil-in-water droplets were observed.

Meanwhile, certain amount of oil-water mixture was accumulated on the bottom of ballast tank (Fig.8). Eventually, part of oil leakage from cargo tank remained in ballast tank. The oil-water mixture increases in ballast space until mixture reached the bottom of internal hull.

On the other hand, the initial height of oil in cargo tank was higher than that of water in basin. Water jet was prevented by oil jet from cargo tank. Based on the Bernoulli's equation mentioned above, the velocity of oil leakage from cargo tank (v_{oil}) and that of the water flowing into ballast tank (v_{water}) are shown as follows:

$$v_{oil} = \sqrt{\frac{2gH_{oil}(t)}{1+\alpha}} \tag{6}$$

$$v_{water} = 0 \tag{7}$$

However, before water and oil interacted with each other, the velocity of oil leakage from cargo tank is still dominated by Eq.6, and the velocity of water from basin can be approximately treated as follow:

$$v_{water} = \sqrt{\frac{2gH_{b-w}}{1+\alpha}} \tag{8}$$

According to Eq. (8), a typical stage is included in the free-leakage stage, which sustained a little time due to the narrow bottom space of ballast tank. This stage is referred to as transient stage in this paper. When the rupture holes were open simultaneously, both oil and water showed typical features of free jet and flowed into bottom space of ballast tank. Then these two jets hit each other. It was featured by violent water-oil interaction. The initial velocity and the momentum brought by oil flow were higher than those of water flow. As a result, the position of water-oil interaction was pushed downward by oil jet, eventually oil leaked into basin.

5.2 Dynamic characteristics of flows in resistance-leakage stage

When the pressure equilibrium was built, the resistance-leakage stage ended. Compared with free-leakage stage, the area of side space of ballast tank is far smaller than that of bottom space of ballast tank. Thus the height of oil-water mixture in side space of ballast tank increased sharply as plotted in Fig.10.

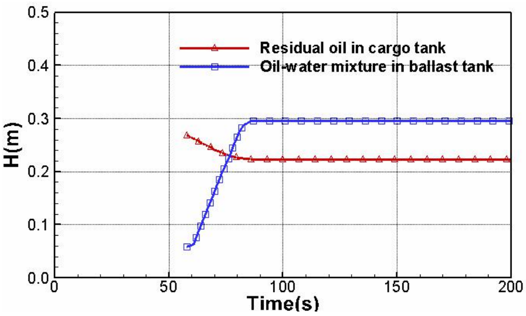


Fig.10 Time histories of height of residual oil in cargo tank (H_{oil}) and that of the oil-water mixture in ballast tank (H_{mixture}) in resistance-leakage stage

The height of residual oil in cargo tank changed slightly (Fig.10), while the volume of residual oil in cargo tank and oil leakage from cargo tank changed dramatically and nonlinearly (Fig.11).

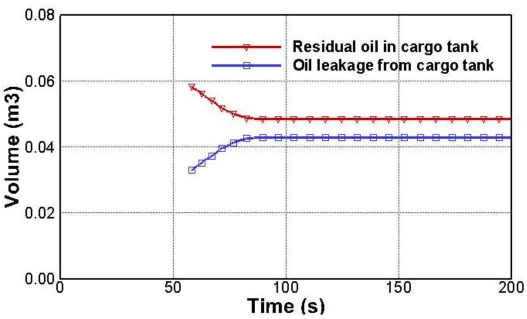


Fig.11Time histories of volume of residual oil in cargo tank and oil leakage from cargo tank in resistance-leakage stage

When oil-water mixture in ballast tank reached and covered internal hole, oil flow through internal hole might be affected by the height of residual oil in cargo tank, the height of oil-water mixture in ballast tank and the draught of model tank. Before the pressure equilibrium was built, the velocity of oil leakage from cargo tank (v_{oil}) is also acquired by the Bernoulli's equation (Eq.6) and is shown as follow.

$$v_{\text{oil}} = \sqrt{\frac{2g[H_{\text{oil}}(t) - H_{\text{mixture}}(t) + 0.06]}{1+\alpha}} \tag{9}$$

As the height of residual oil in cargo tank dropped, the velocity of oil outflow through the internal and external hole decreased. Therefore, dropping oil jet through external hole was weakened and eventually disappeared due to the decrease of pressure difference between inside and outside external hole

Although the height and volume of residual oil in cargo tank were almost constant, the process of oil leakage still continued. When pressure equilibrium was built gradually, the phenomenon of oil-water emulsification was obvious. Flows of oil and water in ballast tank were more complicated in this stage due to turbulence caused by the narrow space of ballast tank.

However, the pressure of external hole in outer basin was higher than that in ballast tank due to inertia of oil flow, so the water and oil in basin flowed into ballast tank in this time. But there was not oil leakage into basin and. At 125s approximately, this flow characteristics disappeared. In the overall process of oil leakage from cargo tank, the phenomenon of water flowing into ballast tank was found in the transient stage and the process of pressure equilibrium built gradually. But, the volume of water in ballast tank was very little due to a shorter time of water flowing into ballast tank. Furthermore, considering tension and the viscous of flow, water was not evenly distributed in bottom space of ballast tank. Certain amount of oil leakage from cargo tank was captured by ballast tank. And the final state presented in Fig.12 well illustrates the behavior of ballast tank in reducing the volume of oil leakage from damaged DHT.

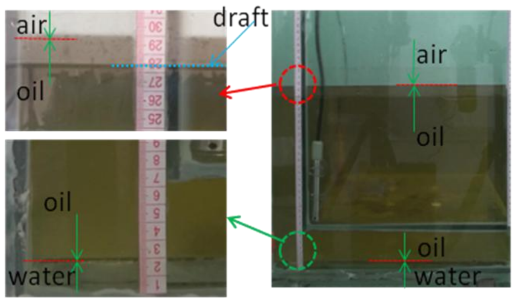


Fig.12 Balanced state at the end of process of oil leakage

6. Conclusions

A series of model tests were carried out to investigate the process of oil leakage from damaged double hull tanker. The dynamic analysis is presented in order to explore the leakage resistance mechanism of ballast tank space. Meanwhile, the behavior of oil captured by the ballast tank is well described based on dynamic analysis. More importantly, hydrodynamic features of flow associated with different stages were captured.

The results show that when bottom space of ballast tank is not filled with the mixture of water and oil, dominate factor of oil leakage from cargo tank is gravity because cargo tank and ballast tank are exposed to atmospheric pressure. While the different height between oil in cargo tank and mixture in double hull is the reason that the internal hole is blocked by the mixture, but flow characteristics are more complex in ballast tank due to the effect of turbulence, viscosity, and air bubbles. Based on the dominated factors presented above, optimization of structure design can be adapted to reduce the volume of oil leakage into the sea.

The unsteady Bernoulli's equation considering the head loss is used in predicting the process of oil leakage from cargo tank. Comparison between the present numerical and the experimental results shows good agreement when viscous coefficient α is 0.8. It implies the importance of viscous effect on oil leakage from damaged DHT which can reduce oil leakage into the sea water. If only considering the assumption of non-viscous, analysis of oil leakage may have significant errors. Therefore, further exploration on oil leakage from DHT is vital important under consideration of viscous effect.

Acknowledgments

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