Hydrodynamic characteristics of an air-suction system of oil spilled in the marine environment

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Abstract

The hydrodynamic characteristics of air-suction system of oil are studied experimentally in order to suck oil with less quantity of water. The air-suction system of oil is set up with a high-speed air-fan, a separating box of oil from water, various types of inlets and transporting pipes. The tested inlets are a straight inlet, a Bell mouth and a contracted inlet. It is concluded that the Bell mouth realizes the desirable suction of oil with slight quantity of water at H/Di = 0.3 for the mineral oil with the kinematic viscosity of 2000 cSt, where Di and H denote the inlet diameter and the height of inlet from the water level respectively.

1 Introduction

The countries such as Japan, which need imports of mineral oils as the major energy source, are daily faced with a danger of oil spill caused by accidents of oil-tankers. It was remembered that the oil-spill accident caused by a sinking of Russian tanker “Navotka”(1997) in Japan sea had given us miserable effects for several years after the accidents [1]. From a long-range viewpoint, the oil pollution in the marine environment seems to be recovered naturally by microbiological activities. However from a viewpoint of short-range viewpoint, the oil spill accident causes significant effects on the marine environment. Thus it is regarded as the best operation to remove oil as soon as possible just after split in the marine environment [2]. It is considered to be the best way to suck oil directly by using water-jet pumps [3]–[7] or air-suction systems, if the ratio of...
the flow rate of oil to water can be made larger considering the post-operation to separate oil from the polluted water.

The purpose of this study is to discuss the air-suction system of oil by using a high-speed air-fan, a separating box of oil from water, and various suction inlets. It should be noted that the water-jet pumps need more quantity of water than the air-suction system and that the air-suction system is regarded to be more suitable than the water-jet pumps in order to suck oil spill.

2 Nomenclature

\[\begin{align*}
A &: \text{cross-sectional area of pipe} \\
C_p &: \text{pressure coefficient} \\
D &: \text{diameter of straight inlet} \\
g &: \text{acceleration of straight inlet} \\
H &: \text{height of inlet from water level} \\
N &: \text{defined by Zivi [8]} \\
P &: \text{pressure} \\
(r, z) &: \text{axisymmetric cylindrical coordinates} \\
R &: \text{radius of straight inlet} \\
Q &: \text{volumetric flow rate} \\
T &: \text{surface tension} \\
u &: \text{flow velocity} \\
\dot{w} &: \text{mass flow rate} \\
\alpha &: \text{ratio of mass flow rate} \\
\varepsilon &: \text{void fraction} \\
\rho &: \text{density} \\
\xi &: \text{hydrodynamic loss coefficient of inlet}
\end{align*}\]

Subscript

\[\begin{align*}
a &: \text{air} \\
i &: \text{at inlet} \\
m &: \text{mean value at the inside of pipe} \\
w &: \text{water} \\
\infty &: \text{at infinity}
\end{align*}\]

3 Experimental apparatus and procedures

Figure 1 shows the experimental apparatus schematically. The oils floating on the water surface in the test tank is sucked up with air and water by the negative pressure of suction air-flow near the suction inlet. The three-phase flow of air-water-oil mixed fluid is transported through the transparent acrylic pipe for flow visualization. In the separating box the oil-mixed water flows down to the discharge tank. The separated air-flow is sucked by the air-fan to be released to the atmosphere via the filter box. The maximum suction pressure and air-flow rate of the air-fan are 2100mmH\text{2}O and 0.05m^3/s respectively. The diameter of the used pipe is 34mm. The inlet of suction flow are classified into three types,
which are a straight inlet, a Jones & Bell mouth and a contracted inlet. The diameter of these inlets is 13 – 110mm.

![Experimental apparatus diagram]

Figure 1: Experimental apparatus and suction inlets
The head loss $H_i$ and loss coefficient $\zeta_i$ of the inlets may be defined as

$$H_i = \zeta_i \left( \frac{u_m^2}{2g} \right) = \zeta_i \left[ \frac{W_m^2}{2 \rho_m g A^2} \left( \frac{x^2}{\alpha \rho_A} + \frac{(1-x)^2}{(1-\alpha) \rho_W} \right) \right]$$  

(1)

for the air-oil-water mixed flow, where

$$\frac{u_m^2}{2g} = \frac{W_m^2}{2 \rho_m g A^2} \left( \frac{x^2}{\alpha \rho_A} + \frac{(1-x)^2}{(1-\alpha) \rho_W} \right).$$  

(2)

Here the void factor $x$ is given as

$$\alpha = \left[ 1 + \left( 1 + \frac{3}{2} N \right)^{\frac{1}{3}} \left( \frac{1-x}{x} \left( \frac{\rho_A}{\rho_W} \right)^{\frac{1}{3}} \right)^{\frac{2}{3}} \right].$$  

(3)

4 Results and discussions

4.1 Pressure distribution at the water surface

Figure 2 shows the pressure distribution of suction air-flow measured at the flat plate set at the height of water surface. The pressure coefficient $C_p$ is defined as $C_p = (P - P)/(\rho u_m^2/2)$, where $P$ and $u_m$ are the atmospheric pressure and mean velocity of air-flow within the suction pipe respectively. The minimum pressure depends on the height $H$ and the diameter of the inlet $D$ and the minimum pressure appears at $r/R = 0.95$ for $H/D = 0.15$, $0.62$. The minimum pressure decreases according as $H/D$ decreases. Figure 3 shows the typical example of the pressure distributions of suction air-flow measured at the flat plate set at the level of water surface for the various inlets. The tested inlets are a straight inlet, a Bell mouth and contracted inlet.
Figure 3: Pressure distribution at water surface for the various inlets

The height of water surface depends on the pressure imposed by the suction air-flow and may be described as

\[
\frac{d^2z}{dr^2} + \frac{dz}{dr} \left[ 1 + \left( \frac{dz}{dr} \right)^2 \right]^{1/2} \cdot \left[ 1 + \left( \frac{dz}{dr} \right)^2 \right]^{1/2} = \frac{\rho g z}{T}.
\]  

Figure 4 shows one of typical cases of water surface raised by the suction air-flow. The height of water surface is well approximated by the numerical solution to Equation (4).

Figure 4: Typical examples of water surface raised by air-suction flow

4.2 Flow regime of air-sucked water

Figure 5 shows the flow regime of air-sucked water near the inlet above water surface. Water is colored red using rhodamine B for the convenience of flow visualization. The behaviors of sucked water are classified into three types.
according to the inlet height \( H \) from the water level. At \( H/D = 0.6 \), the inlet is fully located under the water surface and thus water itself rises into the suction pipe to the height, which balances with the negative pressure of the air-fan. At \(-0.6<H/D\leq 1.4\), the air-water mixed two-phase flow is sucked up. Above the height of \( H/D \) of 1.4, the water surface rises slightly, but does not sucked into the suction pipe.

Figure 6 shows the typical flow patterns of air-sucked water near the straight inlet, a Bell mouth and the contracted inlet. These inlets suck also the air-mixed water flow at \(-0.6<H/D\leq 1.4\), where \( D_i \) denotes the inlet diameter for all inlets.
4.3 Flow rate of air-sucked water

Figure 7 shows the ratio of water to air-flow rate $Q_w/Q_a$. $Q_w/Q_a$ shows the similar characteristics at $-0.6<H/D<1.4$ according to the flow regime in Figure 5. In this range of the inlet height $Q_w$ decreases according as $H/D$ increases.

![Figure 7: Flow ratio of water to air](image)

Figure 8 shows the $Q_w/Q_a$ vs $H/D_i$ characteristics for the various inlets. When considering the suction of water with less air-flow rate, the Bell mouth is concluded to be the best inlet among these inlets.

![Figure 8: Flow ratio of water to air](image)

4.4 Hydrodynamic loss of the tested inlets

Figure 9 shows the hydrodynamic loss coefficient $\zeta_i$ of the various inlets. $\zeta_i$ of the
Bell mouth shows the lowest value among these inlets at \(3 \times 10^4 < Re < 2 \times 10^5\). Thus the Bell mouth is recommended as the most superior inlet for air- suction of water.

![Figure 9: Hydraulic loss of various inlets](image)

### 4.5 Flow rate of water and oil

Figure 10 shows the \(Q_o/Q_w - H/D_i\) characteristics for the various inlets. The kinematic viscosity of the tested oil is 2000 cSt. At \(-0.2 < H/D_i < 0.1\), \(Q_o/Q_w\) takes a constant value 0.025. In this range, the flow rate of oil is less than the flow rate of water. At \(0.1 < H/D_i < 1.4\), \(Q_o/Q_w\) increases according as \(H/D_i\) increases. It should be noted that \(Q_o/Q_w\) increases rapidly at \(H/D_i = 0.3\) in the case of the Bell mouth. It is concluded that the Bell mouth realizes the desirable suction of oil with small quantity of water at \(H/D_i = 0.3\).

![Figure 10: Flow rate of oil to water](image)
5 Conclusions

The behaviors of water sucked by the high-speed air-fan are classified into three types according to the height of inlet. At $-0.6 \leq \frac{H}{D} \leq 1.4$, the oil-water mixed fluid is sucked up, where $H$ and $D$ denotes the height and the diameter of the inlet. The Bell-mouth inlet realizes the desirable suction of oil with less quantity of water at $\frac{H}{D}=0.3$.

REFERENCES