◉ 硏究論文

기포를 동반한 유동장에서의 냉각원관 주위의 해수동결에 관한 실험적 연구

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An Experimental Study on Sea Water Freezing Behavior Along Horizontal Cooled Cylinder With Bubbly Flow

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Key words : Bubbly flow(기포류), Freezing characteristics(동결특성), PIV(입자영상유속계), Sea water freezing(해수동결)

Abstract

This study was experimentally performed to investigate freezing behavior of sea water along horizontal cooled a circular tube with bubbly flow. The experiments were carried out for a variety of parameter, such as sea water velocity, air-bubble flow rate, and cooled-tube temperature. The shape of freezing layer, freezing rate and salinity of frozen layer were observed and measured. And the flow patterns around cooled tube were visualized using the PIV to analyze the relationship between the flow structure and the freezing characteristics. It was found that the experimental parameters gave a great influence on the freezing rate and the salinity of the frozen layer.

NOMENCLATURE

Q_{air} : air-bubble flow rate, [l/min]
R_f : Dimensionless freezing quantity, [−]
Ti : initial temperature of sea water, [° C]
T_w : temperature of cooled tube, [° C]
Re : Reynolds number($=U_i \cdot D_h/\nu$), [−]
T_f : equilibrium freezing temperature, [° C]
T_o : freezing temperatuer of water, [° C]
U_i : velocity of sea water, [m/s]
X : dimensionless air flow rate ($=W_{air}/(W_{air}+W_l)$), [−]
θ_w : dimensionless temperture ($=(T_f-T_w)/(T_o-T_f)$), [−]

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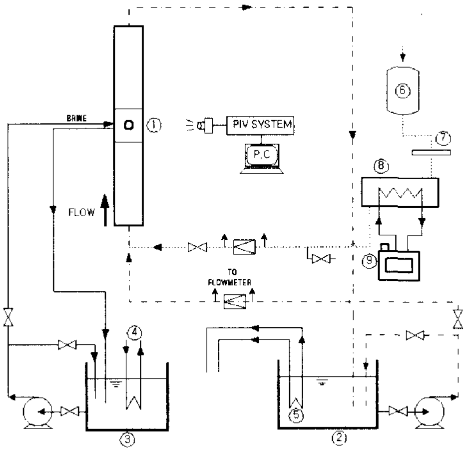
1. INTRODUCTION

One of the most essential things to maintain our lives is water. Water consumption is rapidly increasing due to the exclusive overpopulation, industrial development, and improvement of people' s living quality. However, only 1% of water source is available for human being, so the ever-increasing scarcity of water is getting serious as time goes by. Korea also will be no exception of this tendency and many researches have often proven how urgent Korea is under water deficiency problem. In order to reduce this problem, we try to produce water through constructing multi-functional dams, rainmaking and developing a desalination system(1~2). Among those, the desalination system is expected to be the most effective method because of its availability of seawater. It will enable us to get water easily and steadily. When we select particular kind of desalination system devices, that decision is mostly influenced by fresh water produce cost. In other words, its efficiency depends on whether we can achieve possible energy source easily or not. As environmentally friend means, many people are encouraged to use LNG (Liquefied Natural Gas) in Korea and many countries in the world. Amount of LNG consumption is currently increasing higher. In general, LNG which is stored below −162° C in super-liquid tank requires certain energy to gasify because it is changed into the gaseous state with high pressure wasted cold energy when it is sent to each part in need. LNG loses lots of cold energy (850kJ/kg) during this process of absorbing heat. Therefore, it is necessary to using this wasted cold energy.

The present study is concerned with the freezing heat transfer characteristics along a uniformly cooled a circular tube immersed with a uniform forced flow. The aim is to determine the essential features of the freezing processes, while at the same time providing basic data of practical interest. Sea water is the working flow.

2. EXPERIMENTATION

The experimental apparatus is shown schematically in Fig.1. The device mainly consists of test section, cooling-brine circulating loop, optic system with PIV(Particle Image Velocimetry), and associated measuring systems. The test section is a rectangular duct whose inner dimensions are 200mm wide, 150mm deep, and 1800mm high and is made of transparent acryl plate. A cooled tube was made of copper pipe with 66mm in out diameter, 150mm in length, and 1mm in thickness. And a cooled tube was installed horizontally at the center of the test section. In order to confirm isothermal condition of the cooled tube, thermo-



① Test Section
② Test Solution Tank
③ Brine tank
④ Refrigerator
⑤ Brine Line
⑥ Compressor
⑦ Filter
⑧ Cooler
⑨ Ref. Bath Circulator
——— Brine Line
------- Air Line
—·—·— Sea Water Line

Fig. 1 Schematic of experimental apparatus couples(C-A type) were attached to three points(upper, side, lower) of the tube surface. Also, thermo-couples were installed at the inlet of the test section and the air injection nozzle to control the temperature of the sea water and the air bubble.

The sea water adopted in the present experiment was 3.5wt% NaCl aqueous solution, which was a mixture of fresh water and refined salt. The mean velocity of sea water flow with 0.02m/s, 0.05m/s, and 0.1m/s were adopted. And 10, 20, and 30l/min were adopted as the air-bubble flow rate. After the sea water and air adjusted to a fixed temperature and flow rate, the experiments were started with circulating of cooling brine. During the experiment process the shape of freezing interface and flow pattern around cooled tube were extensively observed and visualized by photographs and PIV(3).

The freezing rate was calculated by measuring of thickness of the ice layer with the lapse of time. The end of the experiment is defined as when the growth of the frozen layer cease, that is, when the heat flux between freezing interface and the cooled tube balanced. After finishing of experiment, the salinity of the frozen layer was measured.

3. RESULT AND DISCUSSION

3.1 The Freezing Behavior of Sea Water over Cooled-Tube

Fig.2 shows the flow characteristics of sea water around the freezing interface, as visualized with PIV for $U_i=0.05$m/s, $Q_{air}=30l$/min. As shown in the figure, the fluid velocity of sea water increases from the forward stagnation point toward the rear of the cooled tube, the reversal flow is occurred at the rear of the cylindrical frozen layer, and the boundary layer develops toward the downstream region(4). The foregoing flow characteristics strongly influence the freezing rate and the salt concentration of the frozen layer. The sea water cooled with the downward flow along the cooled tube begins to be frozen on the upper part of the cooled tube, the frozen layer grows and covers the whole part of cooled tube in a

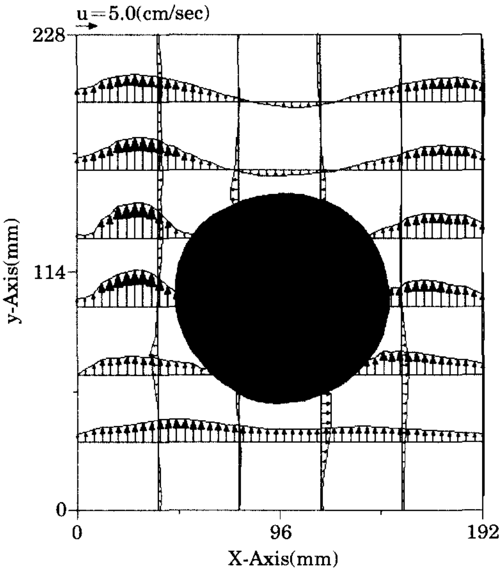


Fig. 2 Time-mean velocity porfile around a cooled tube

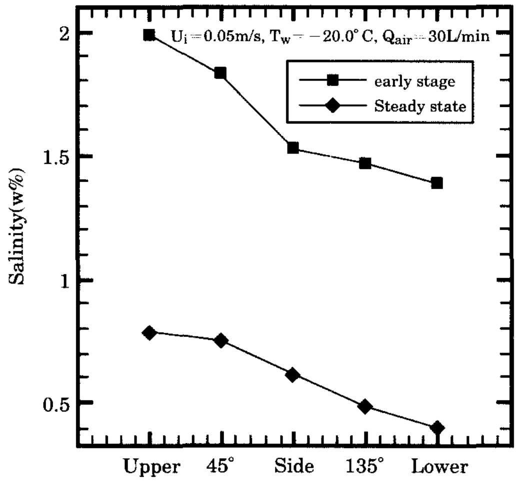


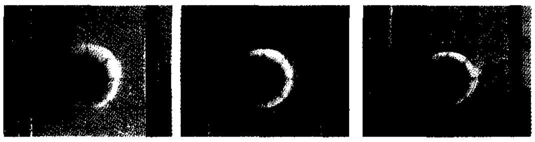
Fig. 3 Distribution of salinity in the frozen layer ; $U_i=0.05$m/s, $T_w=-20.0$°C, $Q_{air}=30l$/min

moment, and the freezing rate in the initial stage of the run is very high because the temperature gradient of the freezing interface is large in that time(5~6). As the time elapses, the frozen layer of the upper part grows faster than the side and lower part of the cooled-tube in which both the heat-transfer coefficient at the freezing interface and the effect of bubble flow are high(7~8). And when the heat balance between the freezing interface and the cooled tube is achieved, the growth of the frozen layer ceases and the freezing behavior is reached in the steady state.

Fig.3 shows the distribution of salinity in the frozen layer. It is seen in the figure that the salt concentration of the frozen layer is high in the early stage of run. The reason for this tendency may be that both the concentration and the amount of the segregated solution from the freezing interface increase in the early stage with the high freezing rate, thus the precipitation rate of the segregated solution within the frozen layer increases. In addition, it is seen in the figure that the salt concentration of the frozen layer decreases toward the lower part of the frozen layer. This may be attributed to the fact that the freezing rate decreases toward the lower part of the cooled-tube.

3.2 The Effect of Fluid Velocity

Fig.4 is the photograph that shows the effect of fluid velocity on the growth of frozen layer. It can be seen from the figure that the thickness of the frozen layer decreases with an increase of fluid velocity.



(a) $U_i = 0.02$m/s (b) $U_i = 0.05$m/s (c) $U_i = 0.1$m/s

Fig. 4 Effect of fluid velocity on freezing behavior

Fig.5 presents the freezing quantity variation with time for different fluid velocity. As mentioned in the above, the volume of frozen layer increases rapidly in the initial stage of the run and ceases after the steady state. From the figure, it is seen that the volume of frozen layer increases with a decrease in fluid velocity. This characteristic may result from the fact that the heat-transfer coefficient at the freezing interface increases with increasing fluid velocity.

Fig.6 illustrates the effect of fluid velocity on the salt concentration of the frozen layer, which is measured except the frozen layer in the initial stage of freezing. As shown in the figure, the salt concentration decreases with increasing fluid velocity. This may be attributed to the fact that the segregated solution, which is washed away from the freezing interface, increases with an increase in fluid velocity.

However, as shown in the Fig.7, it is seen that the mean salt concentration of the frozen layer in the steady increases with an increase in fluid velocity. This characteristic may result from the fact that the growth of frozen layer decreases

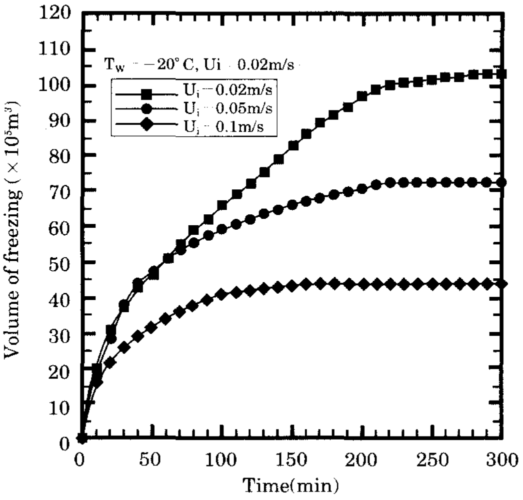


Fig. 5 Effect of fluid velocity on volume of freezing ; $Q_{air} = 10l$/min, $T_w = -20°$ C

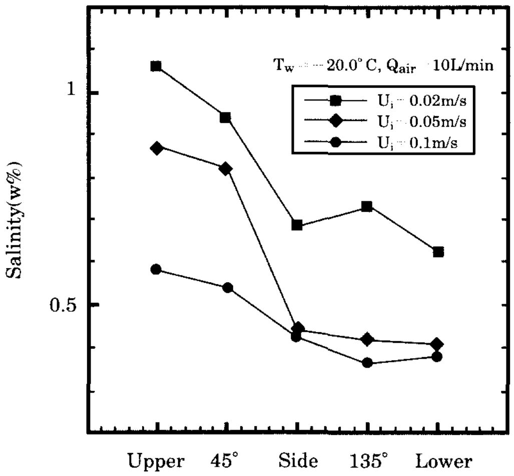


Fig. 6 **Salinity of external frozen layer in the steady state**
; $Q_{air} = 10l/min$, $T_w = -20°C$

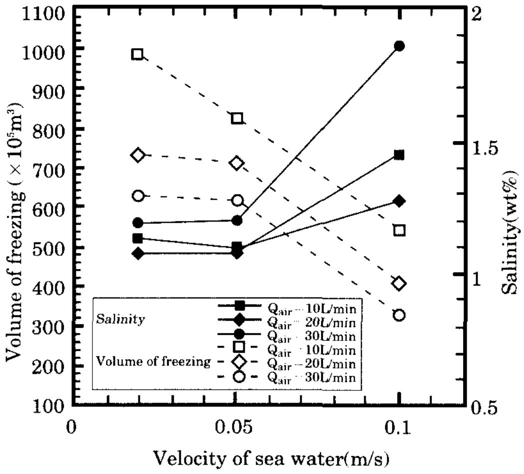


Fig. 7 **Mean salt concentration of frozen layer**
; $T_w = -20°C$

with increasing fluid velocity and the frozen layer of the initial running stage of the run, which has high salt concentration, strongly influences the mean salt concentration of the frozen layer.

3.3 The Effect of Air-Bubble Flow Rate

The effect of air-bubble flow rate on the freezing behavior is shown in Fig.8. As shown in the picture, the thickness of the frozen layer extremely decreases with increasing air-bubble flow rate. This fact may be considered that the heat-transfer coefficient at the freezing interface increases with an increase in air-bubble flow rate. As the air-bubble flow rate increases, the surface of the frozen layer gets to be hard and transparent.

(a) $Q_{air} = 10l/min$ (b) $Q_{air} = 20l/min$ (c) $Q_{air} = 30l/min$

Fig. 8 **Effect of air-bubble flow rate on freezing behavior**
; $T_w = -20°C$, $U_i = 0.02m/s$

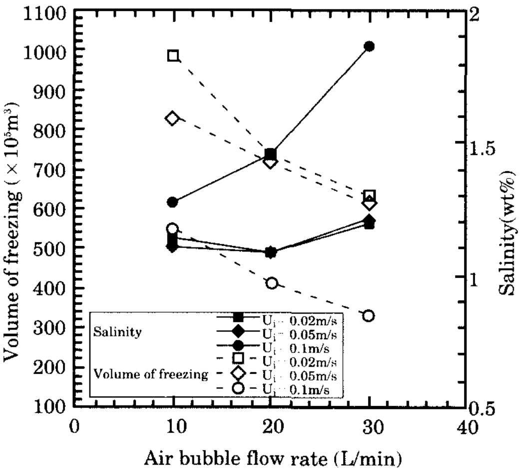


Fig. 9 **Mean salt concentration of frozen layer**
; $T_w = -20°C$

Fig.9 presents the effect of air-bubble flow rate on the mean salt concentration at the frozen layer. It can be seen from the figure that the mean salt concentration of frozen layer in the steady state increases with an increase of the air-bubble flow rate. As represented earlier in Fig.6 and Fig.7, this characteristic may be explained by the following reason: the salt concentration except the frozen layer at the initial running stage decreases with an increase of the air-bubble flow rate because the segregtated solution, which is washed away from the freezing interface, increases with an increase of the air bubble flow rate; on the other hand, the volume of frozen layer decreases with an increase of the air-bubble flow rate, so that the frozen layer at the initial running stage, which has high salt concentra-tion, strongly influences the mean salt concentration of the frozen layer, thus causing the mean salt concentration of the frozen layer to increase.

3.4 The Effect of Cooled-Tube Temperature

Fig.10 shows the effect of cooled-tube temperature on the freezing behavior. It can be seen from the figure that the thickness of the frozen layer decreases with an increase of the cooled-tube temperature. This may be attributed to the fact that the temperature gradient of the freezing interface decreases with an increase of the cooled-tube temperature at the transient-state freezing.


(a) $T_w = -20°C$ (b) $T_w = -15°C$ (c) $T_w = -10°C$

Fig.10 Effect of cooled tube temperature on freezing behavior
; $Q_{air} = 10 l/min$, $U_i = 0.02 m/s$

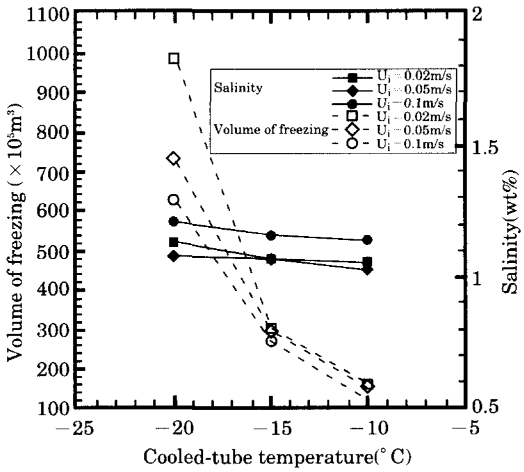


Fig.11 Mean salt concentration of frozen layer
; $U_i = 0.02 m/s$

The effect of cooled-tube temperature on the mean salt concentration at the frozen layer is shown in Fig.11. As shown in the figure, the mean salt concentration decreases with an increase of the cooled-tube temperature. The reason for this tendency may be considered to be that the precipitation rate of the segregated solution at the freezing interface increases with high freezing rate related to a decrease in cooled-tube temperature.

3.5 Correlative Equation of the Freezing Quantity

As a result of present experiment it was found that the sea water freezing quantity may be expressed by the following formula consisting of dimensionless such as, the Renolds number Re, air flow rate X, temperature θw.

$$R_f = f(\theta_w, Re, X) \tag{1}$$

The data of freezing quantity around cooled

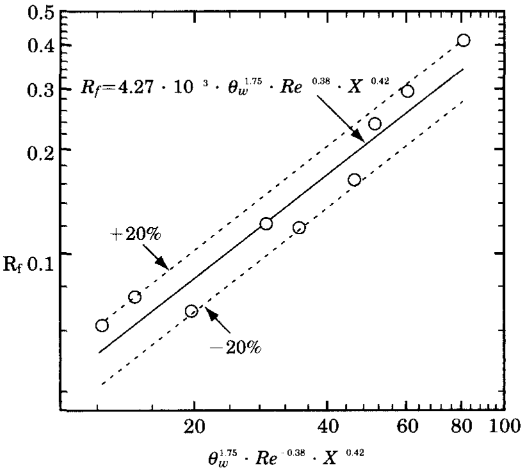


Fig.12 Dimensionless frozen quantity

tube are presented in Fig.12. For the range of parameters covered in the present investigation, the following correlative equation is applicable with a relative error of ±20%.

$$R_f = 4.27 \cdot 10^{-3} \cdot \theta_w^{1.75} \cdot Re^{-0.38} \cdot X^{-0.42} \qquad (2)$$

4. CONCLUSION

An experimental investigation was performed on the effect of fluid velocity, air-bubble flow rate, and cooled-tube temperature on both the freezing rate and the salt concentration of the frozen layer over a horizontal cooled cylinder in a vertical rectangular duct with sea water flow. The following conclusions may be drawn within the experimental range of parameters examined in the present work.

(1) At the initial stage of the sea water freezing, both the freezing rate and the salt concentration of the frozen layer are very high.

(2) The volume of the frozen layer increases with to a decrease in fluid velocity, air bubble flow rate, and cooled-tube temperature.

(3) The salt concentration of external frozen layer decreases with increasing fluid velocity and increasing air bubble flow rate.

(4) The mean salt concentration of steady-state frozen layer increases with an increase in fluid velocity, an increase in air-bubble flow rate, and a decrease in cooled-tube temperature.

(5) For the range of parameters covered in the present investigation, the following correlative equation is applicable with a relative error of ±20%.

$$R_f = 4.27 \cdot 10^{-3} \cdot \theta_w^{1.75} \cdot Re^{-0.38} \cdot X^{-0.42}$$

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