

Numerical Analysis and Experiment of Starfined Vaporizer for Liquefied Natural Gas

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Abstract: LNG Vaporizers must be smaller, more efficient, and easier to operate and maintain. Recently, the vaporizers with greatly enhanced performance as compared to conventional type have been developed to fulfill these requirements. This paper was studied for optimum design of the used vaporizer at a satellite station. Generally, the moisture freezing of air is created by temperature drop under 0°C on vaporizer surface. This problem is increasingly appeared as time passed and humidity rise. In addition, the moisture freezing makes an ice layer and heat transfer on vaporizer is decreased by the ice layer form into the adiabatic condition. By this reason, recent vaporizer system is installed as parallel type, and it takes tree times of vaporizer capacity. But this vaporizer system has much installation costs and is restricted by some space. To solve this problem is very important, and main impacts of vaporizer can be the circumference distance or angle between fin and fin, length, thickness, materials, temperature conditions inner vaporizer and so on. This paper was carried out the numerical analysis and experiment to get the optimum design information of vaporizer fin for liquefied natural gas with super low temperature. The geometry of numerical analysis and experiment were identical. Used parameters are the circumference distance or angle between fins, and fin thickness of vaporizer. Results on numerical analysis were represented about the correlations with the ice layer thickness of vaporizer surface according to the temperature variations inner vaporizer, fin thickness and circumference distance between fins of vaporizer. These results were also verified by experimental study. Finally, the information for optimum design of vaporizer was proposed with correlation equations in this paper.

Keywords: LNG, super low temperature, vaporizer

NOMENCLATURE

D_o : outside diameter of vaporizer tube [mm]
 t/s : ratio of fin thickness by circumference distance of outside diameter between fins
 Φ (or s): angle or circumference distance of outside diameter between fins [°]
 TH_f (or t): thickness of vaporizer fin [mm]
 T_{FE} : temperature of fin end point [°C]
 T_{IN} : inner working fluid temperature of vaporizer [°C]
 R : a radius of vaporizer tube [mm]

1. INTRODUCTION

Recently, many Korea researchers have been concentrating on the super low temperature fields due to the increasing demand of the LNG which has many applications like quick freezing, a power generation by cold energy, low temperature refrigeration and so on.^[1-2] LNG consists of CH₄ as main component, which is made by cooling and pressurization process of natural gas. LNG is carried and saved as a liquid

below -162°C from the outside. But, LNG must be vaporized for using like fuels in industries and home and so on, and then cold energy was generated about latent heat of 120kcal/kg and sensible heat of 80kcal/kg, while the vaporization process. In fact, much additional cost and facilities are demanded for vaporization of LNG.^[3-4] Therefore, this utilization of cold energy and develop of vaporizer is very important. Generally, the vaporization method of LNG is compartmentalized into two types. One is to use the air of atmosphere and another is to use the sea water. The sea water type is used in LNG undertaking station require much heat quantity, however it has some problems to make ice on vaporizer surface in sea water. The vaporizer used at the satellite station is almost by the air vaporization method. In case of air type, the freezing moisture of air is created by temperature drop under 0°C on vaporizer surface, too. This problem is increasingly appeared according to rising of time and humidity. In addition, the freezing moisture makes ice layer and heat transfer on vaporizer decrease by the ice layer formation form into the adiabatic condition.^[5] Because of this reason,

recent vaporizer system is installed as parallel type, and it takes three times of vaporizer capacity. But this vaporizer system requires much installation costs and larger space. Therefore, LNG vaporizer system must be smaller, more efficient, and easier to operate and maintain. But, Korea is in the initial stages of super low temperature fields as vaporizer and utilization technologies of cold energy about LNG, which are lacked of data on the physical and theoretical of super low temperature fields.

The geometry of vaporizer in this paper likes one of vaporizer at the satellite station which is star fin-tube type. Additionally, the geometry change of this vaporizer determine to promote the heat transfer and ice layer formation. Accordingly, parameters such as circumference distance or angle between fin and fin, thickness of fin and temperature conditions of working fluid inner vaporizer were adapted in this study. Liquefied natural gas was supposed as working fluid inner vaporizer, and outside of vaporizer was assumed to be heated by ambient air. Ultimate purpose of this study is to get information of optimal design of vaporizer such star fin-tube which can be used in LNG satellite station by prediction of ice layer thickness on vaporizer surface through numerical analysis. As one of results, optimal ratio of t/s as thickness of fin by outside diameter circumference distance between fins was proposed this paper

2. NUMERICAL ANALYSIS

Using vaporizer in LNG satellite station is distinguished from general heat changers of industry. For adequate vaporization of LNG, the supplied flow-rates of LNG, the conditions of air such as humidity and velocity of air, the geometries of fin like width, length and spacing were very important. Therefore, the numerical model of vaporizer this paper was presented in Fig. 1.

Fig. 1 shows the numerical models of vaporizer according to angle or circumference distance between fins, and TH_F means the thickness of fin which is 2mm, 4mm, 6mm, and T_{IN} as inner working fluid temperature of vaporizer is given each temperature such -162°C , -120°C , -80°C , -40°C , -20°C .

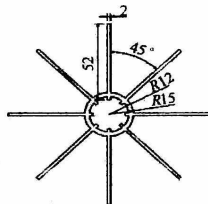


Fig 1: Geometry of vaporizer models for numerical analysis

Above numerical model are two dimensions, and assumed that fin and tube are pure aluminium. Two dimensions model of Vaporizer was not considering the effect of gravity because it supposed horizontal section about vertical arrangement of vaporizer. Also, inner working fluid of vaporizer is always kept on the

selected temperature, and the conditions of ambient air have temperature of 20°C , pressure of 1.013bar. Hence, heat conduction equation of steady state was only used in this paper because it is calculated by temperature difference due to no effect of gravity and no flow of mass. First of all, main assumption of this study is that ice layer on vaporizer surface is formatted from surface temperature of vaporizer to 0°C of surrounding.

For this study, creating surface of numerical model was carried out by using CAD, and creating grid as hexahedral mesh was made by ICEM-CFD software. Lastly, the calculation of model for numerical analysis was accomplished by STAR-CD such common CFD code. The grid system for the calculation zone was shown Fig. 2 and used grid numbers were required about 40,000.

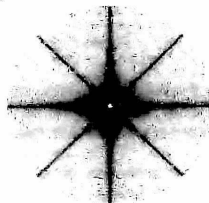


Fig 2: Grid system for the calculation zone

3. NUMERICAL ANALYSIS RESULTS & DISCUSSIONS



Fig 3: Actual photograph of ice layer formation of the general vaporizer

Fig. 3 shows a picture of using vaporizer in LNG satellite station. Ice layer formation between fins on vaporizer surface thickly presented in Fig. 3. Therefore, the thickness of ice layer and end point temperature of fin length in numerical study can be presented like Fig. 4 leading to variation of the circumference distance or angle of between fins, working fluid temperature like LNG and fin thickness.

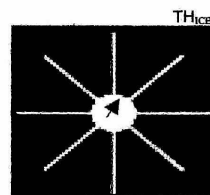


Fig 4: A part of the calculated ice layer thickness and end point temperature of fin on each vaporizer

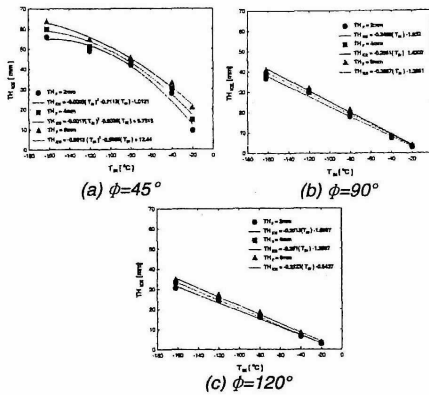


Fig 5: Ice layer thickness according to variation of fin thickness and inner temperature on vaporizer with each other different angle between fins

Fig. 5 shows the thickness of ice layer formation according to fin thickness, inner temperature of vaporizer with different angle between fins, and horizontal axis presents inner working fluid temperature of vaporizer. As shown, thickness of ice layer was decreased when the angle between fins and the working fluid temperature inner vaporizer grow larger, and it has also the increasing trend due to rise of the fin thickness. However, comparing the thickness difference of ice layer about different fin thickness, the case $\Phi=45^\circ$ shows the decreasing of ice thickness difference to -80°C after thickness difference increased with temperature grow of inner working fluid. On the other hand, ice thickness difference of the case $\Phi=90^\circ$ and $\Phi=120^\circ$ were gradually decreased with temperature grow of inner working fluid.

Table 1: summary of numerical analysis results

$T_{in}/^\circ\text{C}$	t/s	TH_{ice}/mm	$T_{in}/^\circ\text{C}$	$\Phi/^\circ$	t/s	TH_{ice}/mm
-162	0.0637	30.5	-153	120	2	
	0.0949	34.72	-154.9	90	2	
	0.1274	39.26	-157	120	4	
	0.1699	56	-155.7	45	2	
	0.1699	58.8	-158.2	90	4	
	0.1911	34.72	-158.6	120	6	
	0.2548	40.65	-159.3	90	6	
	0.3397	59.93	-158.5	45	4	
	0.5096	62.45	-158.5	45	6	
	0.0637	21.27	-113.9	120	2	
-120	0.0949	29.82	-114.3	90	2	
	0.1274	24.97	-116.5	120	4	
	0.1699	48.89	-115.3	45	2	
	0.1699	30.75	-117.2	90	4	
	0.1911	26.98	-117.5	120	6	
	0.2548	31.62	-118	90	6	
	0.3397	51.2	-117.4	45	4	
	0.5096	54.48	-118.2	45	6	
	0.0637	15.83	-75.84	120	2	
	0.0949	18.0	-76.24	90	2	
-80	0.1274	16.21	-77.62	120	4	
	0.1699	41.81	-76.75	45	2	
	0.1699	18.92	-78.1	90	4	
	0.1911	18.15	-78.31	120	6	
	0.2548	21.24	-78.66	90	6	
	0.3397	43.56	-78.21	45	4	
	0.5096	45.31	-78.74	45	6	

40	0.0637	6.3	-37.5	120	2
	0.0949	7.375	-37.77	90	2
	0.1274	6.78	-38.66	120	4
	0.1699	27.83	-38.1	45	2
	0.1699	8.16	-38.9	90	4
	0.1911	8.06	-39.04	120	6
	0.2548	8.57	-39.2	90	6
	0.3397	30.37	-38.95	45	4
	0.5096	32.83	-39.27	45	6
	0.0637	2.77	-18.37	120	2
20	0.0949	3.01	-18.54	90	2
	0.1274	3.07	-19.12	120	4
	0.1699	9.45	-18.75	45	2
	0.1699	3.36	-19.28	90	4
	0.1911	3.37	-19.37	120	6
	0.2548	3.75	-19.49	90	6
	0.3397	14.82	-19.31	45	4
	0.5096	20.6	-19.52	45	6

Therefore, ice thickness from more than $\Phi=90^\circ$ was hardly affected by the variation of fin thickness according to the temperature increase of the inner working fluid. Here, we can find that a vaporizer model with fin thickness of 2mm was well suited. And, the ice thickness was affected by the angle(Φ) or circumference distance(s) between fins more than fin thickness(t). This result was guessed due to effect by decrease of some space between fins. Accordingly, ratio of t/s as fin thickness by outside diameter circumference distance between fins was presented with the correlation equations about ice layer thickness according to temperature variation in Table 2.

Table 2: Correlation equations of ice layer thickness according to inner temperature variation of vaporizer

t/s	Correlation Eq.	$T_{in}/^\circ\text{C}$	t/s
0.0637	$TH_{ice} = -0.2013(T_{in}) - 1.8567$	120	2
0.0949	$TH_{ice} = -0.2468(T_{in}) - 1.832$	90	2
0.1274	$TH_{ice} = -0.261(T_{in}) - 1.3697$	120	4
0.1699	$TH_{ice} = -0.0023(T_{in})^2 - 0.7113(T_{in}) - 1.0121$	45	2
0.1699	$TH_{ice} = -0.2861(T_{in}) - 1.4202$	90	4
0.1911	$TH_{ice} = -0.2223(T_{in}) - 0.5437$	120	6
0.2548	$TH_{ice} = -0.2857(T_{in}) - 1.2651$	90	6
0.3397	$TH_{ice} = -0.0017(T_{in})^2 - 0.8035(T_{in}) + 5.7613$	45	4
0.5096	$TH_{ice} = -0.0012(T_{in})^2 - 0.5095(T_{in}) + 12.44$	45	6

Fig. 6 shows the correlation between the ice layer thickness and ratios of t/s according to the LNG temperature. In this study, geometries of same ratio is t/s , one is the vaporizer in case of $\Phi=45^\circ$ and $TH_F=2\text{mm}$, and the others are $\Phi=90^\circ$ and $TH_F=4\text{mm}$. All of both have the same ratio of $t/s=0.1699$ however the ice thickness by numerical results are different each other. The ice layer thickness in case $\Phi=90^\circ$ and $TH_F=4$ was presented less than the case $\Phi=45^\circ$ and $TH_F=2\text{mm}$, which can be known in Fig. 7(a). Also, $t/s=0.1699$ ($\Phi=90^\circ$ and $TH_F=4\text{mm}$), $t/s=0.2584$ ($\Phi=45^\circ$ and $TH_F=4\text{mm}$) and $t/s=0.5096$ ($\Phi=45^\circ$ and $TH_F=6\text{mm}$) had relatively high ice thickness than others. By this reason, the heat transfer and efficiency of vaporizer must be considered apart from the vaporizer geometries is t/s of 0.1699, 0.2584 and 0.5096, additionally the ice thickness in case of all was not increased by increasing of t/s ratios but general ice thickness by increasing of t/s ratios show the increasing tendency.

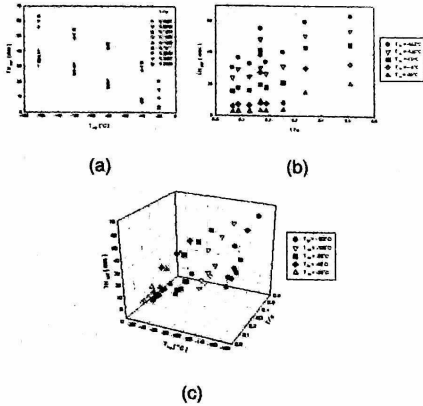


Fig 6: the ice layer thickness of vaporizer surface according to the increase of LNG temperature and ratios of t/s

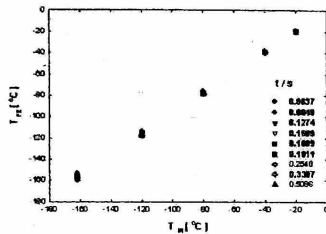


Fig 7: End point temperature distributions of vaporizer fin according to the increase of LNG temperature and ratios of t/s

Fig. 7 shows the end point temperature distributions of vaporizer fin according to the increase of LNG temperature and ratios of t/s . to increase of fin end point by temperature increase of working fluid is general a fact. Therefore, the temperature of fin end point was increased with the increasing of vaporizer inner temperature, in the contrary the temperature difference of fin end point by the variation of t/s ratios was reduced according to inner temperature increase of vaporizer the increasing of vaporizer inner temperature. additionally the fin end temperature in case of $t/s=0.0637$ was presented the best high temperature. Order of the fin end temperature in respect to t/s ratios is:

0.0637($\Phi=120^\circ$ and $TH_F=2mm$) >
0.0849($\Phi=90^\circ$ and $TH_F=2mm$) >
0.1699($\Phi=90^\circ$ and $TH_F=4mm$) >
0.1274($\Phi=120^\circ$ and $TH_F=4mm$) >
0.1699($\Phi=45^\circ$ and $TH_F=2mm$) >
0.3397($\Phi=45^\circ$ and $TH_F=4mm$) >
0.1911($\Phi=120^\circ$ and $TH_F=6mm$) >
0.2548($\Phi=90^\circ$ and $TH_F=6mm$) >

0.5096($\Phi=45^\circ$ and $TH_F=6mm$)

Accordingly, the correlation equations about ice layer thickness according to LNG temperature variation were summarized in Table 3.

Table 3: Correlation equations of fin end point temperature according to inner temperature variation of vaporizer

t/s	Correlation Eq.	$\Phi [^\circ]$	$TH_F [mm]$
0.0637	$T_{EP} = 0.9493(T_{IN}) + 0.4412$	120	2
0.0849	$T_{EP} = 0.9505(T_{IN}) + 0.6287$	90	2
0.1274	$T_{EP} = 0.9713(T_{IN}) + 0.2035$	120	4
0.1699	$T_{EP} = 0.9645(T_{IN}) + 0.4814$	45	2
0.1699	$T_{EP} = 0.9783(T_{IN}) + 0.2349$	90	4
0.1911	$T_{EP} = 0.9805(T_{IN}) + 0.1878$	120	6
0.2548	$T_{EP} = 0.9846(T_{IN}) + 0.1745$	90	6
0.3397	$T_{EP} = 0.9802(T_{IN}) + 0.2588$	45	4
0.5096	$T_{EP} = 0.9859(T_{IN}) + 0.1647$	45	6

4. EXPERIMENT

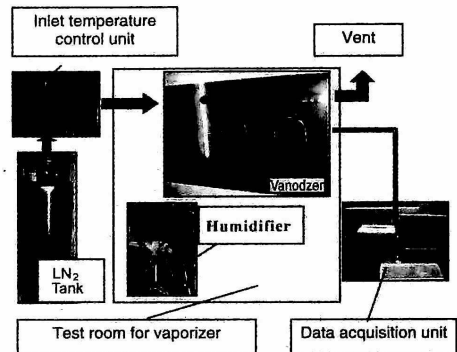


Fig 8: Experimental setup for vaporizer

Fig. 8 shows the experiment system of vaporizer according to angle or circumference distance between fins, and the thickness of fin which is 2mm and T_{IN} as inner working fluid temperature of vaporizer is given each temperature such -170°C , -120°C , -80°C , -40°C . The working fluid is LN_2 .

Above experiment system are inlet temperature control unit and LN_2 tank and humidifier and data acquisition unit

Fig. 9-18 shows the vaporizer model for experiment which has ratio $TH_F=2mm$. Inner working fluid of vaporizer for experiment was used the liquefied nitrogen which has a low boiling point of -196°C at 1atm. However, for identical temperature condition like working fluid of numerical analysis, the nitrogen temperature of -162°C was constantly maintained by controlling of heating coil. The testing room has temperature of 20°C and air humidity of 50%. The material of physical vaporizer is A6063S and has

excellent heat conductivity. T-type thermocouple was installed at fin end point to get fin end temperature according to time.



Fig 9: Test model of Finless.

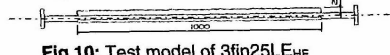


Fig 10: Test model of 3fin25LE_{HF}

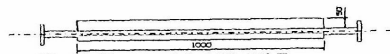


Fig 11: Test model of 3fin50LE_{HF}

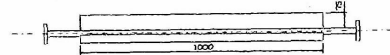


Fig 12: Test model of 3fin75LE_{HF}

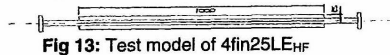


Fig 13: Test model of 4fin25LE_{HF}



Fig 14: Test model of 4fin50LE_{HF}



Fig 15: Test model of 4fin75LE_{HF}



Fig 16: Test model of 8fin25LE_{HF}



Fig 17: Test model of 8fin50LE_{HF}

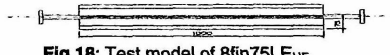


Fig 18: Test model of 8fin75LE_{HF}

Fig. 19 – 22 show measured temperature profile to various type and temperature. Flow rate is 0.5kg/min. shows the end point temperature distributions of vaporizer fin according to the increase of LN₂ temperature to increase of fin end point by temperature increase of working fluid is general a fact. In the various model, present 4fin50LE_{HF} have most efficient according to temperature grade in Table 4.

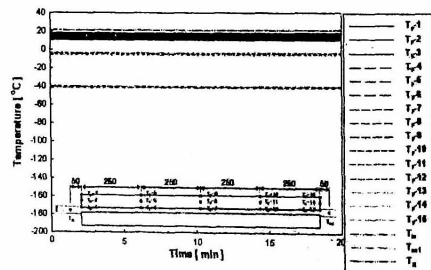


Fig 19: Measured temperature profile to 4fin50LE_{HF}, Q=0.5kg/min, T_{IN}=-40°C, HUM.=50%

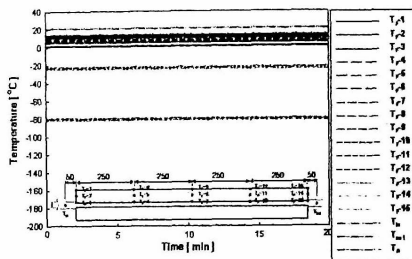


Fig 20: Measured temperature profile to 4fin50LE_{HF}, Q=0.5kg/min, T_{IN}=-80°C, HUM.=50%

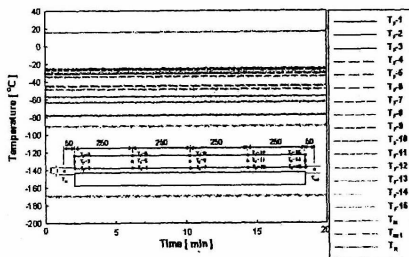


Fig 21: Measured temperature profile to 4fin50LE_{HF}, Q=0.5kg/min, T_{IN}=-120°C, HUM.=50%

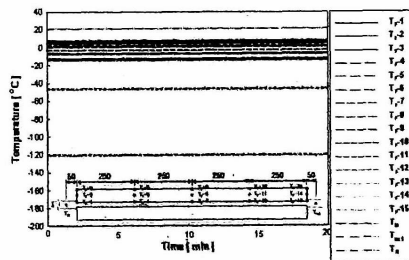


Fig 22: Measured temperature profile to 4fin50LE_{HF}, Q=0.5kg/min, T_{IN}=-170°C, HUM.=50%

Table 4: Grade of various types on the Outlet temperature at Inlet temperature of -170°C

Type	Inlet temperature	Outlet temperature	Grade
Finless	-170°C	-132°C	7
3fin25LE _{HF}	-170°C	-154°C	8
3fin50LE _{HF}	-170°C	-160°C	8
3fin75LE _{HF}	-170°C	-78°C	1
4fin25LE _{HF}	-170°C	-158°C	8
4fin50LE _{HF}	-170°C	-91°C	3
4fin75LE _{HF}	-170°C	-88°C	8
8fin25LE _{HF}	-170°C	-161°C	10
8fin50LE _{HF}	-170°C	-92°C	4
8fin75LE _{HF}	-170°C	-98°C	5

5. COMPARISON VERIFICATION OF NUMERICAL ANALYSIS & EXPERIMENT

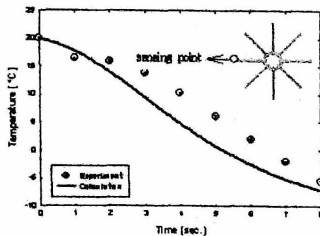


Fig 23: the fin end temperature distributions of the experiment and calculation according to time at the working fluid temperature of -162°C

Fig. 23 shows the temperature distributions of fin end on the experiment and calculation result with respect to time. The experimental result takes about 6.5 sec to reach 0°C , and the numerical result takes 5 sec to reach 0°C . Like this, the heat transfer before ice layer formation rapidly occurred by supplying of much heat quantity from outside. But, the heat transfer after ice layer formation will be reduced by effect of it. And, the time difference between experimental and numerical results reaching 0°C is 1.5 sec. Although the numerical result is faster than experiment, the temperature distribution pattern of the numerical result is well met with the experiment, and this can be known by comparing the graph in Fig. 11.

6. CONCLUSION

Numerical analysis and experiment for the optimum design and the prediction of the ice layer formation on the vaporizer fin has been carried out

1) By increasing of the fin thickness and decreasing of angle or circumference distance between fins, the heat transfer on vaporizer of the initial stage of vaporizer operating can be promoted due to grow of heat transfer area but it in late stage was predicted to reduce by increasing of the ice layer thickness.

2) Considering initial stage and late stage of vaporizer operating, $t/s=0.849$ (i.e. $\Phi=90^{\circ}$ and $TH_F=2\text{mm}$) was evaluated as optimum geometry of others. And, the geometries are allowed to change according to circumstances in range of t/s ratios, excluding $t/s=0.1699$ ($\Phi=90^{\circ}$ and $TH_F=4\text{mm}$), $t/s=0.2584$ ($\Phi=45^{\circ}$ and $TH_F=4\text{mm}$) and $t/s=0.5096$ ($\Phi=45^{\circ}$ and $TH_F=6\text{mm}$).

3) Ratio of t/s as fin thickness by outside diameter circumference distance between fins was defined in this paper, and quantitative values of the information about the ice layer thickness and fin end temperature according to LNG temperatures and $0.0637 \leq t/s \leq 0.5096$ were obtained.

4) The correlation equations of the ice layer thickness and fin end temperature according to LNG temperature variation were proposed. The numerical

result was verified by comparison with experimental result and was agreed with experiment.

5) In the experiment models, 4fin50LE_{HF} type have most efficient according to outlet temperature grade.

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