Springer

Journal of Mechanical Science and Technology 22 (2008) 981~990

Journal of Mechanical Science and Technology

www.springerlink.com/content/1738-494x

Experimental study on the characteristics of longitudinal fin air-heating vaporizers in different seasons

Hyo Min Jeong[1], Han Shik Chung[1,*], Eldwin Djajadiwinata[2], Pil Hwan Kim[2] and Yong Hun Lee[3]

[1]*School of Mechanical and Aerospace Engineering, the Institute of Marine Industry, Gyeongsang National University, 445 Inpyeong-dong, Gyeongsang-namdo 650-160, Korea.*

[2]*Graduate School, Department of Mechanical and Precision Engineering, Gyeongsang National University, 445 Inpyeong-dong, Gyeongsang-namdo 650-160, Korea.*

[3]*Department of Mechanical and Precision Engineering, Gyeongsang National University, 445 Inpyeong-dong, Gyeongsang-namdo 650-160, Korea*

(Manuscript Received March 2, 2007; Revised December 13, 2007; Accepted December 23, 2007)

Abstract

Air-heating vaporizers are usually used to regasify LNG at satellite areas because of the small demand for natural gas there. The common type of air heating vaporizer which exists in the market is the longitudinally finned type with 8 fins, 50mm fin length and 2mm fin thickness. To contribute in developing an efficient air-heating vaporizer, experiment on finned type air-heating vaporizer using 8 fins, 50mm fin length with 2mm fin thickness (8fin50le) -which exist in the market- and 4 fins, 75mm fin length with 2mm fin thickness (4fin75le), which is proposed, were conducted. Then, both types of vaporizers are compared. The experiments were conducted in one hour by varying the ambient condition and the length of the vaporizer. The ambient air was controlled so that it has the same condition (same temperature, humidity and air velocity) with air condition in every season available and the length was varied 4000mm, 6000mm and 8000mm for each type of vaporizer. Additional experiment with longer duration, i.e., 4 hours and in a single room condition was conducted to validate the previous result. In this experiment, the main aspects in analyzing the characteristics of the air heating vaporizer are the inlet-outlet enthalpy difference and the outlet temperature of the working fluid. LN_2 is used to substitute LNG for safety reasons. The results show that the characteristics of the finned type 4fin75le vaporizer are comparable to the finned type 8fin50le vaporizer.

Keywords: LNG (Liquefied Natural Gas); LN_2 (Liquid Nitrogen); Vaporizer; Fin; Super low temperature

1. Introduction

Liquefied natural gas (LNG) is natural gas (NG) that has been cooled to the point that it condenses to a liquid, which occurs at a temperature of approximately –161℃ and at atmospheric pressure. Liquefaction reduces the volume by approximately 600 times, thus making it more economical to transport between continents in specially designed ocean vessels. Hence, LNG technology makes natural gas available throughout the world. At the present time, world demand for LNG is increasing. This can be seen in Fig. 1 [1].

To return LNG to a gaseous state, it is fed into a regasification plant. The LNG is warmed by passing it through pipes heated by direct-fired heaters, seawater or through pipes that are in heated water. These devices are known as ‘vaporizers’. The vaporized gas is then regulated for pressure and enters the pipeline system as natural gas. Finally, residential and commercial consumers receive natural gas for daily use from local gas utilities or in the form of electricity.

But for inland areas, where pipelines do not exist or

*Corresponding author. Tel.: +82 55 640 3185 Fax.: +82 55 640 3188
E-mail address: hschung@gnu.ac.kr
DOI 10.1007/s12206-007-1216-1

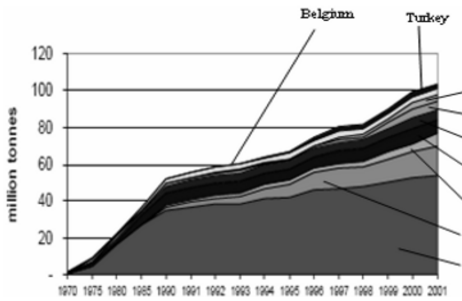


Fig. 1. Growth in LNG demands.

are difficult to construct, the LNG is delivered to the inland-receiving terminal available at that area, regasified and delivered to consumers. At inland-receiving terminals, air heating vaporizer type is usually used, because the demand for natural gas in inland/satellite areas is small. Besides that, the construction and running costs of this type of vaporizer are low and it has the simplest operation system. The constraint of this type of vaporizer is its small to medium production capacity due to the small heat capacity of air as its heat source [2]. Therefore, to meet the NG increasing-demand at inland areas, research for developing the best performance of air heating vaporizer should be conducted.

A vaporizer actually is a heat exchanger. One of the main problems that occurs in a heat exchanger is frost formation due to condensation and freezing of water vapor contained in the air. These ice deposits will cause a decrease in heat transfer rate because the thermal conductivity of ice is less than one-fortieth that of aluminum alloy. The thicker the ice becomes, the less the heat transfer efficiency. In addition, when fins are covered with thick ice (for finned type vaporizer) until their configuration becomes almost invisible, the effective heat transfer area decreases [3]. Lee et al. [4] conducted experiments to find the effects of various factors (fin pitch, fin arrangement, air temperature, air humidity, and air velocity) on the frost growth and thermal performance of a fin-tube heat exchanger. General solutions for optimum dimensions of convective longitudinal fins with base wall thermal resistances were solved analytically by Chung et al. [5]. Yang et al. [6] conducted research to find optimal values of the design parameters for a fin-tube heat exchanger of a household refrigerator under frosting conditions. Seker et al. [7, 8] conducted research both numerically and experimentally, on the frost formation on fin-and-tube heat exchangers.

Experiments with finless type and finned type vaporizers of 4 fins 75mm long and 8 fins 50mm long had been conducted at constant room temperature by Lee et al. [9]. Kong et al. [10] conducted numerical analysis in order to find the best fin shape.

Now, this paper tries to compare, by experiment, the heat transfer performance of vaporizers with 8 fins 50mm long to vaporizers with 4 fins 75mm long which operate in various seasons. The 8 fin type is taken because it is the common type which exists in the market. The 4 fin type of vaporizers are taken based on the numerical analysis conducted by Jeong et al. [11] with a little modification on the length to increase the heat transfer area. Jeong et al. [11] concluded that the optimum vaporizer geometry is a vaporizer which has an angle between fins of 90^o and fin thickness of 2mm. It means the vaporizer is using 4 longitudinal fins. This is because it has the optimum heat transfer rate if the presence of frost deposit is considered. On the other hand, they also concluded that without the presence of frost deposit, the decrease of angle between fins, which means the fin quantity increases, will increase the heat transfer rate due to the increase of heat transfer area.

2. Heat transfer basic theory

From Newton's law of cooling we know that the average convection heat transfer coefficient is proportional to the convection heat transfer rate. Hence:

$$\dot{Q} = hA_{os}\left(T_{\infty} - T_{m,os}\right) \; ; \; if \;\; T_{m,os} < T_{\infty} \tag{1}$$

And, because the flow in a tube (and a vaporizer is actually a long tube) is completely enclosed, an energy equation may be applied to determine the convection heat transfer rate in terms of the difference in temperatures at the tube inlet and outlet. If the mass flow rate is constant and assuming that fluid kinetic and potential energy changes are negligible, there is no shaft work and regarding Cp as constant, the energy equation is

$$\dot{Q} = \dot{m} \;\; Cp \;\; \left(T_{m,out} - T_{m,in}\right) \tag{2}$$

From Eqs. (1) and (2) we get

$$\dot{m}\,Cp\left(T_{m,out} - T_{m,in}\right) = h_o\,A_{os}\left(T_{\infty} - T_{m,os}\right) \tag{3}$$

These equations show us that if the mass flow rate is constant, the increase of ambient or room temperature (T_{∞}) will also increase the heat transfer rate, which will also increase the tube outlet temperature

($T_{m,out}$). In other words, the room temperature is proportional to the tube inlet-outlet temperature difference, ΔT.

3. Eperimental setup

The experimental setup (Fig. 2) consists of four parts:

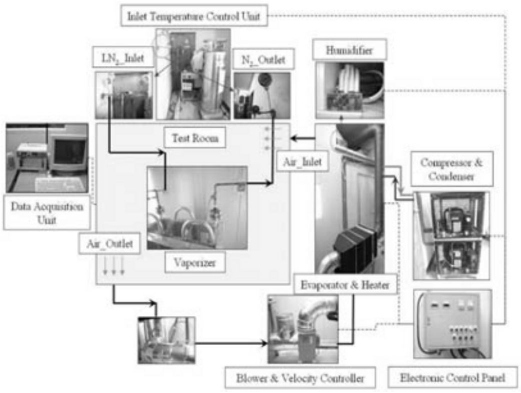


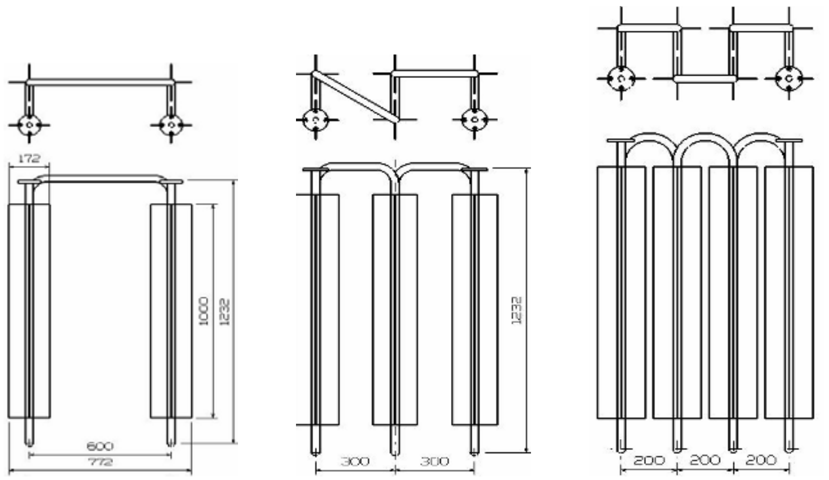
Fig. 2. Schematic diagram of experimental setup for vaporizer system.

(1) Test Room
(2) Room conditioning unit
(3) Data acquisition unit
(4) Electronic control unit

The vaporizer is located in a room, called the test room, which size is 1.99m × 1.34m × 2.9m. The condition of the test room is maintained by using a room conditioning unit so that it has the same condition with the season average condition available in Tong Young City, South-Korea. This data was taken from the government, Korea Meteorological Administration official website [12]. Liquid nitrogen (LN_2) was used instead of LNG in this experiment for safety reasons.

The vaporizers are made of aluminum alloy. Thermocouples are inserted every 500mm to measure the temperature of the Nitrogen inside the vaporizer. All of these temperature data were recorded with a data logger. The type of thermocouple used is K-Type with an uncertainty of 2.2℃ or 2% (whichever is greater) when measuring temperature below 0℃.

The experiment was conducted at four different



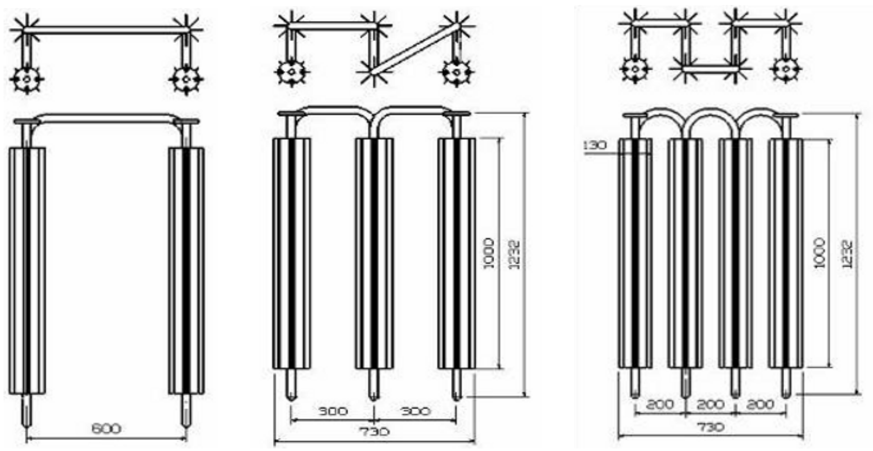
(a) 4000mm (b) 6000mm (c) 8000mm

Fig. 3. Drawing of the test vaporizer of finned type 4fin75le vaporizer.

Fig. 4. Basic pipe shape of the finned type 4fin75le used.

Table 1. Experimental vaporizers used and season conditions setting.

		8fin50le			4fin75le		
		4000mm	6000mm	8000mm	4000mm	6000mm	8000mm
Spring	Temperature (K)	285			285		
	Relative Humidity (%)	65			65		
	Air velocity (m/s)	2.5			2.5		
Summer	Temperature (K)	303			303		
	Relative Humidity (%)	80			80		
	Air velocity (m/s)	2			2		
Autumn	Temperature (K)	290			290		
	Relative Humidity (%)	70			70		
	Air velocity (m/s)	2.5			2.5		
Winter	Temperature (K)	273			273		
	Relative Humidity (%)	55			55		
	Air velocity (m/s)	3			3		



(a) 4000mm (b) 6000mm (c) 8000mm

Fig. 5. Drawing of the test vaporizer of finned type 8fin50le vaporizer.

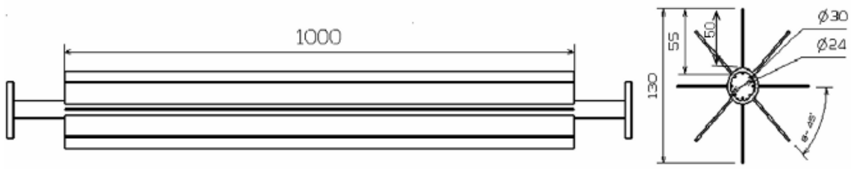


Fig. 6. Basic pipe shape of the finned type 8fin50le used.

conditions for each length. Those conditions were spring, summer, autumn and winter conditions. The types of vaporizer used in the experiment were finned type with 4 fins, 75mm fin length (Fig. 3 and Fig. 4) and finned type with 8 fins, 50mm fin length (Fig. 5 and Fig. 6). The notation for the former finned type is 4fin75le and for the latter is 8fin50le. Note that for finned type 8fin50le, the fins protrude 50mm outward from the outer surface of the pipe and 2mm inward from the inner surface of the pipe. Thickness of the pipe is 3mm. And for finned type 4fin75le, the fins protrude 75mm outward from the outer surface of the pipe and 2mm inward from the inner surface of the pipe. Thickness of the pipe is 3mm. The lengths which were tested for each type of vaporizer were 4000mm, 6000mm and 8000mm. The type of vaporizer, length and condition of seasons used in the experiment can be seen in Table 1.

Table 2. Δh_{max} and Δh_{actual} of the vaporizers.

		Inlet-outlet enthalpy difference (kJ/kg)			
		Spring	Summer	Autumn	Winter
Max	---	195.2	214.0	200.4	182.7
8fin50le actual	4000mm	171.8	187.8	176.5	130.0
	6000mm	180.2	202.5	192.9	174.3
	8000mm	191.1	207.4	197.6	179.9
4fin75le actual	4000mm	168.2	187.4	174.7	154.7
	6000mm	185.2	205.7	190.2	169.5
	8000mm	193.4	211.4	195.2	182.2

The room conditioning unit consisted of dehumidifier, heater, refrigerator and humidifier. The electronic control unit controlled the operation of these room conditioning devices so that the devices operated automatically when needed.

If the temperature of the test room is higher than the set-temperature, the refrigerator will operate and the heater will stop. If the opposite condition happens, the heater will operate and the refrigerator will stop. The humidifier and dehumidifier also operate reversely one to another, depending on the humidity of the test room. Before starting the experiment, we set the air-velocity to be the same as the season condition using a valve located on the ducting. The air velocity was measured with a digital velocity meter, the uncertainty of which is 3% of reading or 0.015m/s (whichever is greater).

In this experiment the inlet pressure was maintained constant at 2 bar absolute with a pressure regulator. The flow rate was 0.39-0.43kg/min. The flow rate was measured by dividing the change of the LN_2 tank weight with the time duration of the experiment. The experiment was held in 60 minutes and the data was taken every 6 seconds by means of data acquisition system.

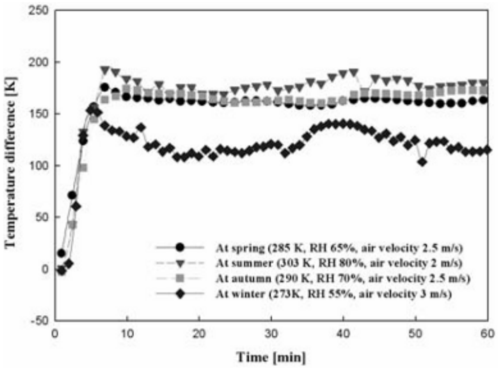
The inner diameter of the vaporizer tube was 24mm and the outer diameter was 30mm. The inlet temperature was constant at 99.1K ± 4.6%. This temperature was naturally achieved when the inlet pressure was held constant at 2 bar absolute and the outlet pressure was atmospheric pressure.

To validate the result of the main experiment explained above, an additional experiment of 8fin50le and 4fin75le type of 8000mm long was conducted by using the same setup in longer time duration, i.e., 4 hours with air conditions at 293K, 65% and 2.5 m/s of temperature, relative humidity and air velocity, respectively. The inlet pressure was also 2 bar absolute and the outlet pressure was atmospheric pressure. The mass flow rate was 0.37kg/min. All of the uncertainty values stated in this study are a combination of calibration error of the device and random error.

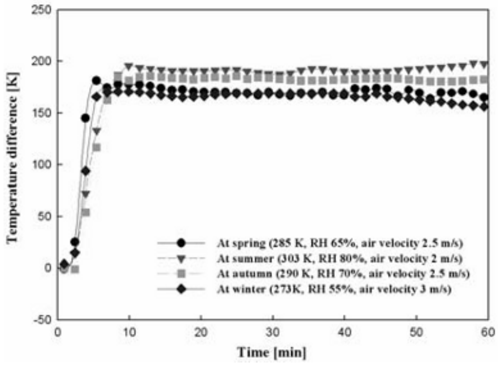
4. Results and discussions

In this study, the heat transfer rate is represented by the enthalpy difference of LN_2 inlet and outlet. The enthalpy is taken from NIST, NIST on-line Thermo physical Properties of Fluid System, with ASHRAE Standard State Convention [13].

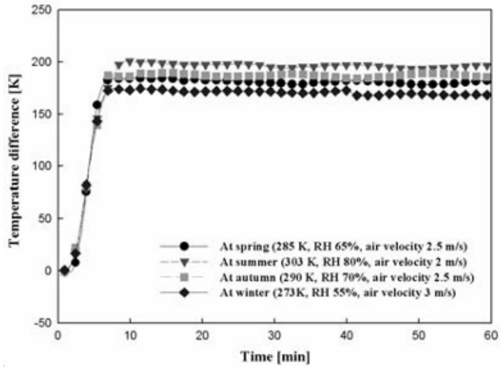
From the graph of time versus inlet-outlet temperature difference in different season for the 8fin50le, (Fig. 7), it can be seen that the graphs are nearly steady or slightly decreasing. Although an ice deposit has formed on the vaporizer, it doesn't really influence its performance for the one hour experiment because of the existence of the fins. So, more time is needed for the ice deposits to cover all of the vaporizer's surface. Besides that, Lee et al. [4] found that the ice-like frost nuclei generated during the crystal growth period act as a small fin, which results in the increase in roughness and surface area. During the frost layer growth period, frost nuclei grow to form a porous frost layer, and the thermal insulation effect of the frost layer increases because it acts like a thermal insulator. Based on this statement, it is concluded that for a one hour experiment, the porous frost layer is formed on the vaporizer area near the inlet, which will cause a decrease of the heat transfer rate. But on the vaporizer area near the outlet, crystal frost is formed which will cause an increase of the heat transfer rate (Fig. 8). Generally speaking, when a porous frost layer is formed on the upstream of vaporizer surface, crystal frost is formed on the downstream vaporizer surface. Hence, these two opposite phenomena cancel each other so that the decrease of av-



(a) 8fin50le 4000mm vaporizer



(b) 8fin50le 6000mm vaporizer



(c) 8fin50le 8000mm vaporizer

Fig. 7. Inlet-outlet temperature differences related to time for finned type 8fin50le vaporizers in different seasons.

(a) Frost type near inlet of the vaporizer (porous frost type)

(b) Frost type near outlet of the vaporizer (crystal frost type)

Fig. 8. Pictures of frost types that occurred on the vaporizer.

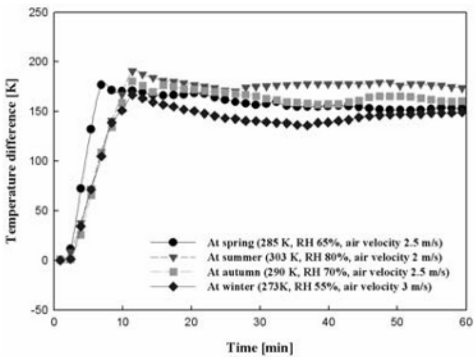
erage heat transfer rate is reduced.

At the beginning of the experiment, when crystal frost starts to form at the inlet area, the average heat transfer rate should increase. This phenomenon cannot be seen on the graphs because it occurs at the transient period to steady condition of the inlet section.

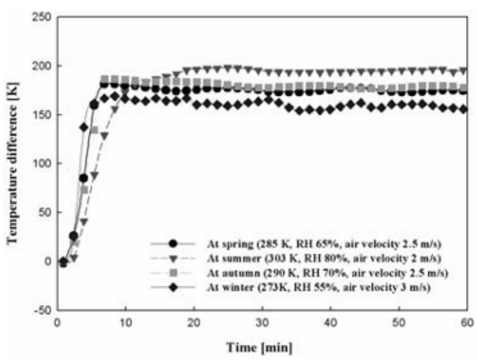
From the experiment conducted by Yan et al. [14], it was found that a higher surface temperature is det-

Table 3. Performance of vaporizers based on Δh.

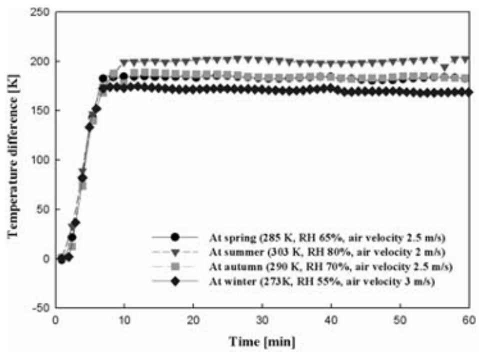
		Performance (%)			
		Spring	Summer	Autumn	Winter
8fin50le	4000mm	88.0	87.8	88.1	71.2
	6000mm	92.3	94.6	96.3	95.4
	8000mm	97.9	96.9	98.6	98.5
4fin75le	4000mm	86.2	87.6	87.2	84.7
	6000mm	94.9	96.1	94.9	92.8
	8000mm	99.1	98.8	97.4	99.7



(a) 4fin75le 4000mm vaporizer



(b) 4fin75le 6000mm vaporizer



(c) 4fin75le 8000mm vaporizer

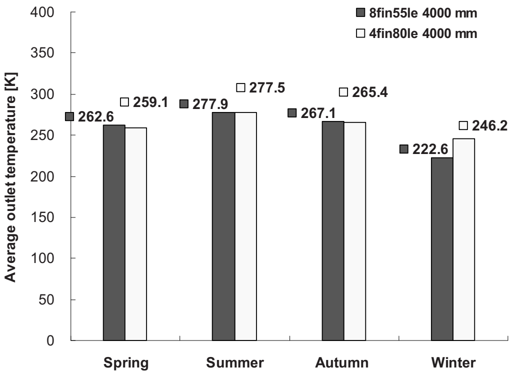
Fig. 9. Inlet-outlet temperature differences related to time for finned type 4fin75le vaporizers in different seasons.

rimental to frost formation, but higher moisture is favorable for frost growth. Therefore, in summer, when the relative humidity is high and the temperature is also high, the ice growth is deteriorated due to the high temperature. On the other hand, in winter, when the temperature is low and the humidity is also low, the ice growth decreases due to the low moisture content in the air. Additionally, the graphs show that the inlet-outlet temperature difference increases if the temperature of ambient air also increases. On the finned type 4fin75le vaporizers, the trend of inlet-outlet temperature differences is the same with the 8fin50le (Fig. 9).

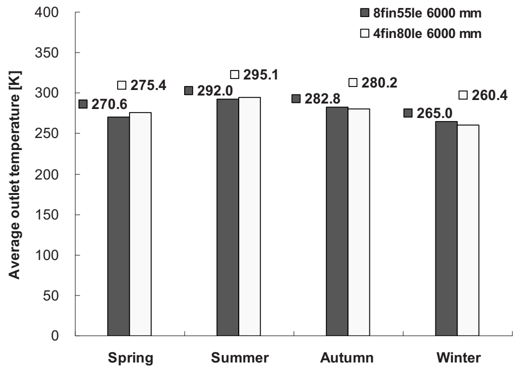
Next, from the experimental results, it is seen that the Δh, which represents the heat transfer rate, of finned type 8fin50le vaporizers are comparable with that on the 4fin75le vaporizers. These phenomena can be observed more clearly from the performance data (Table 3) and the outlet average temperature diagram (Fig. 10). The performance is defined as:

$$\textbf{Performance} = \frac{\Delta h_{act}}{\Delta h_{max}} \times 100\% \tag{4}$$

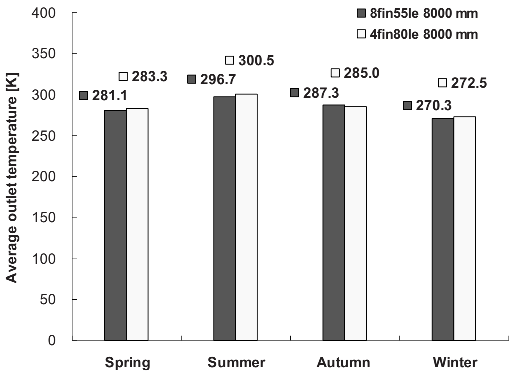
Δh_{max} is the inlet-outlet enthalpy difference of va-



(a) 4000mm vaporizer



(b) 6000mm vaporizer



(c) 8000mm vaporizer

Fig. 10. Comparison of average outlet temperature between 8fin50le type and 4fin75le type vaporizers for different lengths in different seasons.

porizer if the outlet temperature reaches the temperature of ambient air.

Since the performance of these two types of vaporizers is comparable, the proposed vaporizer type is based only on economical considerations. Hence, the 4fin75le is proposed as the better type because its production cost is cheaper than 8fin50le. The amount of material which is needed to produce 8fin50le type vaporizer is more than to produce 4fin75le (the difference is 200mm^3 per unit length). Additionally, Jeong et al. [11] stated that heat transfer rate of an 8 finned type vaporizer will decrease steeper than 4 finned type when the ice formed is getting thicker. It is because the angle between fins of 8 finned type vaporizer is smaller than 4 finned type.

Next, the optimum vaporizer length for each season among the 8fin50le and 4fin75le vaporizers should be taken. They will be evaluated based on the outlet temperature and the length. The shortest length which can achieve an outlet temperature of 273K will be chosen. The temperature 273K is taken as the reference because, on that point, the water vapor contained in the ambient air will not freeze on the outer surface of the delivery pipe or the natural-gas storage tank.

Based on the underlined values in Table 4, the chosen lengths for 8fin50le vaporizers are 8000mm, 4000mm and 6000mm for spring, summer and autumn conditions, respectively. At winter conditions, the outlet temperature must be below 273K because the ambient temperature is 273K. As an approximation, the 8000mm vaporizer is chosen for winter. Then, the chosen lengths for 4fin75le vaporizers are 6000mm, 4000mm and 6000mm for spring, summer and autumn conditions, respectively. For winter, by using the same reason with the 8fin50le vaporizer, the 8000mm vaporizer is chosen. Furthermore, we can conclude that to accommodate the condition at all seasons, the 8fin50le and 4fin75le vaporizers with 8000mm long are chosen as they can fulfill the requirement to reach the minimum outlet temperature of 273K.

Next, in the graphs of the 4 hour experiment (Fig.

Table 4. Average outlet temperature of the vaporizers for every length and season condition.

		Average outlet temperature (K)			
		Spring	Summer	Autumn	Winter
8fin50le	4000 mm	262.6±6.8	*277.9±12.7*	267.1±9.0	222.6±22
	6000 mm	270.6±7.4	*292.0±6.3*	*282.8±4.7*	265.0±13.5
	8000 mm	*281.1±5.2*	*296.7±5.3*	*287.3±4.7*	270.3±7.3
4fin75le	4000 mm	259.1±14.3	*277.5±8.1*	265.4±12.7	246.2±14.5
	6000 mm	*275.4±5.5*	*295.1±4.9*	*280.2±6.6*	260.4±8.6
	8000 mm	*283.3±4.4*	*300.5±5.2*	*285.0±5.5*	272.5±8.6

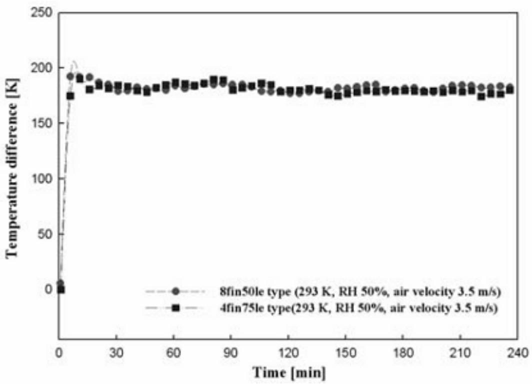


Fig. 11. Inlet-outlet temperature difference versus time of 8000mm long 8fin50le type and 4fin75le type for 4 hours experiment and constant room conditions.

11), 8fin50le type and 4fin75le type of vaporizer show a comparable average heat transfer rate which is represented by the ΔT. The average inlet temperature is 99.4K±3.7% and the average ΔT is 182.1K±4.2% and 180.9K±4.6% for 8fin50le and 4fin75le, respectively. In this figure, a slight decrease of ΔT due to ice formation can be noticed. This shows that the existence of the fins has a bigger contribution, in decreasing the ice deposition effect on the average heat transfer rate, rather than the cancelling phenomenon between the porous frost layer effect and the ice-like frost nuclei (crystal frost) effect.

5. Conclusions

The information from this study can be summarized as follows:

(1) The heat transfer rate on a finned type 8fin50le vaporizer is comparable with that on the 4fin75le vaporizer.

(2) From this study, we know that the frost implantation of the vaporizer surface is affected by air velocity from outside and humidity condition, and also it is affected by supplied flow rate of working fluid and inner temperature also.

(3) In deciding the optimum length of 8fin50le and 4fin75le vaporizer for each season, the shortest length which can achieve an outlet temperature of 273K will be chosen. The temperature 273K is taken as the reference because, on that point, the water vapor contained in the ambient air will not freeze on the outer surface of the delivery pipe or the storage tank.

(4) Through the experiment result at every season condition, the case of 4000mm shows that the 8fin50le model of vaporizer shows a higher temperature compared to 4fin75le. But a length of 6000mm and 8000mm shows that it is rather the 4fin75le model which has higher vaporizer temperature than 8fin50le. Also, we could see if the length is more than 6000mm, the 4fin75le and 8fin50le vaporizer outlet gas temperatures show a temperature distribution of more than 273K.

(5) The working fluid temperature of the gas-liquid field inside the vaporizer is usually constant or decreasing, but it was indicated that the temperature is an increasing and decreasing phenomenon with length direction, periodically; this was a pressure pulsation due to turbulence of fluid inside the vaporizer. Moreover, the gas flow field affects pressure pulsation also.

Acknowledgment

This research was financially supported by the Ministry of Commerce Industry and Energy (MOCIE) and Korea Industrial Technology Foundation (KOTEF) through the Human Resource Training Project for Regional Innovation and the second-phase of Brain Korea 21 Project.

Nomenclature

A_{os} : Tube outer surface area [K]
Cp : Specific heat at const. Pressure [kJ/kg^{o}C]
h_o : Average convection heat transfer coefficient outside the tube [W/m^{2}K]
$\dot{m}$: Mass flow rate [kg/s]
$\dot{Q}$: Heat transfer rate [W]

$T_{m,in}$: Tube inlet mean temperature [K]
$T_{m,out}$: Tube outlet mean temperature [K]
$T_{m,os}$: Tube outer surface mean temperature [K]
T_{∞} : Room or ambient temperature [K]
Δh : Inlet-outlet enthalpy difference [kJ/kg]
$\Delta h_{,act}$: Actual inlet-outlet enthalpy difference of LN_2 [kJ/kg]
$\Delta h_{,max}$: Maximum inlet-outlet enthalpy difference [kJ/kg]
ΔT : Temperature difference (inlet-outlet Temperature difference) [K]

References

[1] M. M. Foss, Chief Energy Economist and CEE Head, Energy Economics Research at the Bureau of Economic Geology, The University of Texas at Austin, Introduction to LNG, An overview on liquefied natural gas (LNG), its properties, the LNG industry, safety considerations (2003).

[2] K. Sugano, LNG Vaporizers, Research and Development, Kobe Steel Engineering Reports, 56, Aug. (2006).

[3] N. Morimoto (Osaka Gas CO., LTD.), S. Yamamoto (Osaka Gas CO., LTD.), Y. Yamasaki (Osaka Gas CO., LTD.), T. Shimokawatoko (Osaka Gas CO., LTD.), K. Shinkai (KOBE STEEL, LTD.), S. Egashira (KOBE STEEL, LTD.) and K. Konishi (Kobelco research institute, INC.), Development and Practical Application of a High Performance Open-rack LNG Vaporizer (SUPERORV).

[4] K. S. Lee and W. S. Kim, The effects of design and operating factors on the frost growth and thermal performance of a flat plate fin-tube heat exchanger under the frosting condition, *KSME International Journal*, 13 (1999) 973-981.

[5] B. T. F. Chung, Z. Ma and F. Liu, General Solutions for Optimum Dimensions of Convective Longitudinal Fins with Base Wall Thermal Resistances, *Proceedings of 11th IHTC*, 5, August 23-28, Kyongju, Korea, (1998).

[6] D. K. Yang, K. S. Lee and Simon Song, Fin Spacing Optimization of a Fin-tube Heat Exchanger under Frosting Conditions, *Int. J. of Heat and Mass Transfer,* 49 (2006) 2619-2625.

[7] D. Seker, H. Karatas and N. Egrican, Frost Formation on Fin-and-Tube Heat Exchangers. Part I - Modeling of Frost Formation on Fin-and-tube Heat Exchangers, *Int. J. of Refrigeration,* 27 (2004) 367-374.

[8] D. Seker, H. Karatas and N. Egrican, Frost Formation on Fin-and-Tube Heat Exchangers. Part II - Experimental investigation of Frost Formation on Fin-and-Tube Heat Exchangers, *Int. J. of Refrigeration*, 27 (2004) 375-377.

[9] Y. H. Lee, S. C. Lee, H. M. Jeong and H. S. Chung, Experimental Study on Gasification Characteristic by using Liquefied Gas Vaporizer with Various Shape, Proceedings of the second *International Conference on Cooling and Heating Technologies, Dalian, China*, July 26-30, (2006).

[10] T. W. Kong, S. C. Lee, Y. H. Lee, H. S. Chung and H. M. Jeong, A Study on the Air Vaporizer for Liquefied Natural Gas with Super Low Temperature, *Proceedings of the 3rd Asian Conference on Refrigeration and Air-conditioning*, Gyeongju, South Korea (2006).

[11] H. M. Jeong, H. S. Chung, S. C. Lee, T. W. Kong and C. S. Yi, Optimum Design of Vaporizer Fin with Liquefied Natural Gas by Numerical Analysis, *KSME Int. J.*, 20 (2006) 545-553.

[12] Korea Meteorological Administration official website (http://www.kma.go.kr/intro.html).

[13] NIST on-line Thermophysical Properties of Fluid System (http://webbook.nist.gov/chemistry/fulid/).

[14] W. M. Yan, H. Y. Li, Y. J. Wu and J. Y. Lin, Performance of Finned Tube Heat Exchangers Operating under Frosting Conditions, *Int. J. of Heat and Mass Transfer,* 46 (2003) 871-877.