

Vaporization Characteristics of Super Low Temperature Liquefied Nitrogen Gas

Sang Chui Lee¹, Tae Woo Kong¹, Sung Su Kim¹, Chul Su Kim²
Han Shik Chung³, Hyo Min Jeong³

¹Graduate School, Department of Mechanical and Precision Engineering, Gyeongsang National University, Tongyeong, KOREA

²Korea Technology Eng. Co., Ltd., Seongnam, KOREA

³School of Mechanical and Aerospace Engineering, Gyeongsang National University, Tongyeong, KOREA

Abstract: This paper was carried out to determine the vaporization characteristics of vaporizer with super low temperature liquid nitrogen gas. Vaporizer used in this experiment is aero fin coil tube type which has inside diameter of 5mm, outside diameter of 6mm. and total length of vaporizer is about 20,000mm. The experimental parameters are air velocity and flow rate of liquefied nitrogen. Temperatures of vaporizer surface were measured by T- type thermocouples. For measuring the surface temperature of vaporizer, the thermocouples were installed every 2,000mm in the vaporizer length direction. The results present temperature transitions and phenomenon on vaporizer surface with respect to the flow rates of liquefied nitrogen and air velocity as time function.

Keywords: vaporizer, heat transfer, liquefied nitrogen, super low temperature

NOMENCLATURE

A : Area of cross-section for air[m²]
g : Acceleration due to gravity[kg-m/s²]
 $\dot{m}_{LN_2}$: Mass flow rate of liquefied nitrogen[kg/min]
P_T : Total pressure[pa]
P_r : Static pressure[pa]
q : Quantity of heat of air
q_{ava} : Average quantity of heat of air
Δt : Time variation of experiment
T : Temperature[°C]
v : Average velocity of air[m/s]
ΔW : Weight variation of LN₂ tank
ρ : Density of air[kg/m³]

1. INTRODUCTION

Recently, researches have been concentrating on the super low temperature field due to the increasing and demand of the liquefied natural gas. which has many applications such as quick freezing, a power generation by cold energy, low temperature refrigeration and so on. Vaporization process required for the use of LNG can be used to obtain such low temperature below -162°C. Accordingly, the studies on the super low temperature liquids like the LNG are very important for the cold energy utilization and vaporizer development.^[1-2]

In previous studies, Nam et al.(2000)^[3-4] carried out evaluation of the heat transfer enhancement and the pressure drop characteristics for liquid nitrogen using wire-coil-insert technique under horizontal two-phase conditions, and a correlation in a power-law relationship of the Nusselt number, Reynolds number and Prandtl number for the heat transfer was

proposed which can be available for designing of cryogenic heat exchanger.

Choi and Chang(1999)^[5] investigated how the frost cryogenic nitrogen and ambient air affects the thermodynamic performance of power and heat transfer was disturbed by implantation of frost, also reported that the cryogenic nitrogen generally increase the surface temperature of most section along flow direction but there are rather the decreasing section. Jang(2001)^[6] researched about the characteristic of vaporization of liquefied nitrogen and then investigated the variation phenomenon of vibration mode during evaporating.

The liquefied nitrogen is often used as one of cryogenic fluids because it is stable at the normal temperature, and liquefied nitrogen is comparatively safety because about 78% of ambient is nitrogen gas which is an inert and no poisonous. Also liquefied nitrogen is cheaper than other cryogenic fluids and has boiling point of -196°C at 1.013bar pressure.

Accordingly, for cold energy utilization and vaporization of super low temperature liquids, the vaporizer was made as aero-fin coil tube type and liquefied nitrogen as working fluid was used. And heating source of vaporizer is ambient air.

This paper was carried out to investigate the vaporization characteristics of super low temperature of liquefied nitrogen by measuring the surface temperature on vaporizer, and discuss with the phenomenon of present experiments and previous studies

2. EXPERIMENTAL SET UP AND METHOD

2.1 Experimental Set up

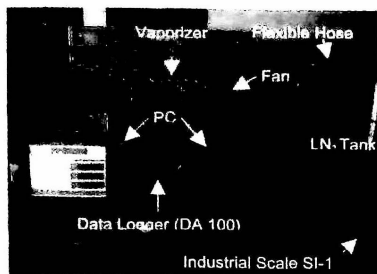


Figure 1: Experimental apparatus of vaporizer system.

Fig. 1 shows apparatus of experimental set up. The chamber and duct were made of acrylic to observe the moisture freezing on vaporizer surface. And the vaporizer and fan were installed in the duct. Liquefied nitrogen tank was installed at upper part of the industrial scale SI-1, therefore we will be able to know supplied flow rate from the liquefied nitrogen tank by measuring amount quantity of weight change.

Table 1 gives geometry specification of vaporizer tube and fin

Table 1: Geometry specification of vaporizer.

Contents	Tube	Fin
Materials	Copper	Aluminium
Inside diameter(mm)	10.00	12.00
Outside Diameter(mm)	12.00	30.00
Thickness(mm)	1.00	0.50
Total Length(mm)	19815.26	-
Total numbers	-	2744
Pitch(mm)	-	4.09

2.2 Experimental method

This paper is based on experiments done with two types of systems. First we discuss the open system, shown in Fig. 2. Here, the ambient air was continuously absorbed and cooled down by the liquid Nitrogen. Afterward the cold air discharged out of the system. Hence, there is a continuous circulation of air and hence the air cooled down to a lesser extent than the closed type systems. Hence, this system can be used to vaporize liquid Nitrogen at faster rate.

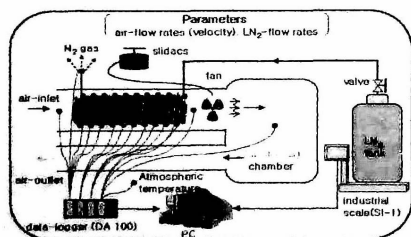


Figure 2: Schematic diagram of open type system.

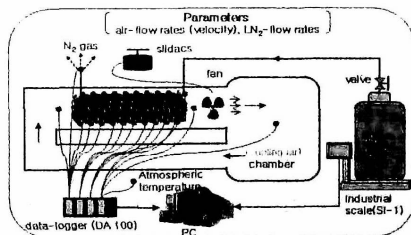


Figure 3: Schematic diagram of close type system.

Figure 3 shows the schematic diagram of close type system. This system doesn't have incoming air. The air inside the system is recycled continuously by fan, leading to a gradual decrease in the air temperature. The advantage of this system is it can obtain air of lower temperature. The parameters of two systems are the velocity of air inside system, which can be changed by varying the fan voltage hence its speed, and flow rate of liquefied nitrogen supplied which can be varied by varying the opening of the supply valve.

2.3 Temperature and flow rate measuring

The temperature of the system was measured at different points by thermocouples of T-type. Measuring points of temperature include 11 points in the vaporizer surface measured by thermocouples marked T_1 to T_{11} . The temperature of air before and after heat exchange was measured by thermocouples marked T_{12} and T_{13} respectively. The temperature of air inside the chamber, nitrogen gas at exit and ambient were measured by thermocouples marked T_{15} , T_{14} and T_{16} respectively as shown in Fig 2 and 3.

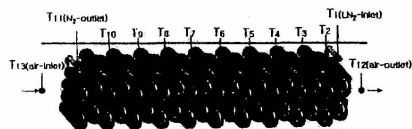


Figure 4: Temperature measuring point on the vaporizer.

The temperature of the vaporizer surface was measured at 11 different points by thermocouples marked from T_1 to T_{11} attached at almost equal intervals along the vaporizer tube with the first and last being attached at the inlet to the vaporizer and its exit as shown in Fig. 4. Two more thermocouples marked T_{13} and T_{12} were attached to air inlet and exit. Measured temperature data was loaded in a data logger (DA 100) which acted as a data recording and acquisition system. After loaded temperature data had a calibration of $\pm 1^\circ\text{C}$, it was saved at eight-second intervals in a personal computer. The air velocity inside system was controlled by voltage controller of the fan which had a voltage range from 0 to 240V. The air velocity assumed constant throughout the entire duct is calculated by the pressure difference between total pressure and static

pressure using a pitot-tube. The equation for air velocity is as follows.

$$v = \sqrt{\frac{2(P_T - P_s)}{\rho}} \quad (1)$$

Flow rate of liquefied nitrogen was measured by the industrial scale SI-1 to contain RS-232C which is linked with personal computer. Following is the equation for flow rate of liquefied nitrogen.

$$\dot{m}_{LN_2} = \frac{\Delta w}{\Delta t} \quad (2)$$

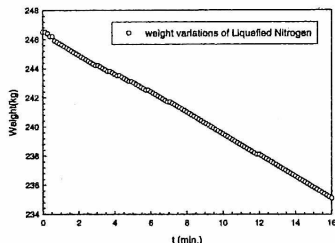


Figure 5: Weight variations of liquefied nitrogen.

Fig. 5 shows the weight of remaining liquefied nitrogen with time, the weight variation shows a constant gradient. Accordingly, this paper uses the average mass flow rate of liquefied nitrogen.

3. THEORETICAL ANALYSIS

3.1 Reasons behind assuming $\Delta h > 0$

Since the Nitrogen is at lower temperature than the ambient, heat will obviously flow into the vaporizer leading to an increase in enthalpy.

Thus $\Delta P < 0$ and $\Delta h > 0$ and hence the effect of $\Delta P < 0$ and $\Delta h > 0$ on the temperature of Nitrogen fluid in the various regions as per Cases 1, 2 and 3 discussed below.

The other assumption is that the initial and final states between which $\Delta P < 0$ and $\Delta h > 0$ are defined are in the same region.

The P-h diagram or Mollier's chart for Nitrogen is shown in the Fig. 6. Now, referring to this diagram a rough of which has been presented below the effect of heat input, phase change, length of vaporizer, associated pressure drops, time which the nitrogen undergoes in the vaporizer etc on the temperature of Nitrogen can be analyzed to get an idea of temperature of Nitrogen along the length of vaporizer.

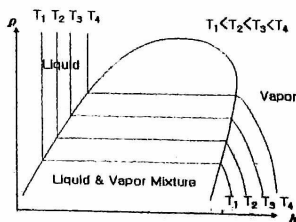


Figure 6: P-h Diagram of nitrogen showing constant temperatures.

3.2 Experimental conditions

Table 2: Experimental conditions

Contents		v (m/s)	$\dot{m}_{LN_2}$ (kg/min)	Humidity (%)	Ambient temperature (°C)
open	test 1	6.93	0.53	58	17.7
	test 2		0.71	78	16.0
	test 3		1.34	46	17.5
close	test 4		0.49	54	17.4
	test 5		1.13	84	17.0
	test 6		1.42	44	18.0
open	test 7	15min 6.93	0.76	48	17.5
		5min 11.99			
		5min 15.99			
close	test 8	15min 6.93	0.80	50	17.0
		5min 11.99			
		5min 15.99			

Experimental conditions of the various tests carried out with open and close type system are shown in Table 2. As shown in Table 2, tests 1 to 3 were conducted with the open type system. In these 3 tests the air velocity is kept constant and only the flow rate of liquefied nitrogen is varied. Tests 4 to 6 were performed on the close type system. Test 7 and 8 are performed by maintaining a constant flow rate of liquefied nitrogen and changing the air velocity. The range of air velocity is 6.93m/s to 15.99m/s.

Referring to the above figure, it can be easily considered the following,

Case 1: Subcooled region

(Case 1.1) $\Delta P < 0$, $\Delta h > 0$: Temperature rises

(Case 1.2) $\Delta h = 0$: Temperature constant

(Case 1.3) $\Delta P = 0$, $\Delta h > 0$: Temperature rises

Case 2: Saturated region

(Case 2.1) $\Delta P < 0$: Temperature falls

(Case 2.2) $\Delta P = 0$: Temperature constant

Case 3: Superheated region

(Case 3.1) $\Delta P < 0$, $0 < \Delta h < (\Delta h)_{critical}$: Temperature falls

(Case 3.2) $\Delta P < 0$, $\Delta h = (\Delta h)_{critical}$: Temperature constant

(Case 3.3) $\Delta P < 0$, $\Delta h > (\Delta h)_{critical}$: Temperature rises

(Case 3.4) $\Delta P = 0$, $\Delta h > 0$: Temperature rises

where $(\Delta h)_{critical} = \Delta h$ due to $\Delta P < 0$ and while moving along a constant temperature line.

Before proceeding further, pressure drop across the valve which lies between the Nitrogen cylinder and the vaporizer should be considered. This process is isenthalpic and occurs in the subcooled region and from Case 1.2, it can be found that the temperature is constant. Though this process occurs before temperature sensing point T_1 , it is of significance as

Nitrogen enters the vaporizer at pressures lower than that in the Nitrogen vessel.

4. RESULT AND DISCUSSION

4.1 Temperature distributions of the open and close type system according to flow rate and time

Fig. 7 shows the temperature distributions of system at $v=6.93\text{m/s}$, $\dot{m}_{\text{LN}_2}=1.34\text{kg/min}$ as test 3 and Fig. 8 shows the temperature distribution of close type system at $v=6.93\text{m/s}$, $\dot{m}_{\text{LN}_2}=1.42\text{kg/min}$ as test 6 (Fig. 7 and 8 have maximum flow-rate of its each system.)

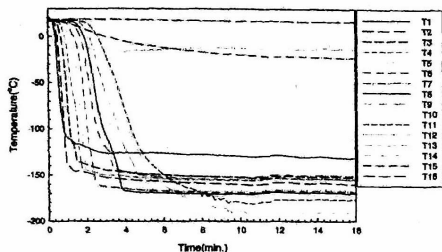


Figure 7: Temperature distributions of open system at $v=6.93\text{m/s}$, $\dot{m}_{\text{LN}_2}=1.34\text{kg/min}$.

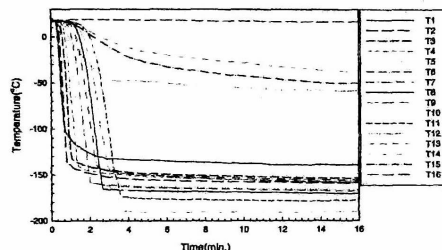


Figure 8: Temperature distributions of close system at $v=6.93\text{m/s}$, $\dot{m}_{\text{LN}_2}=1.42\text{kg/min}$.

In Fig. 7, the temperature distributions of T_{13} and T_{16} were similar to each other and be constant by the time because T_{13} shows the temperature of ambient and T_{16} shows the temperature of inflow air inside system. But T_{13} in case the closed system as Fig. 8 was decreased by recycling of air inside system. By comparing the temperature difference between T_{12} and T_{13} , open type absorbs more quantity of heat because the temperature difference of open type system is larger than it of close type system. However, open type system can not have lower temperature of air inside chamber than close type system. For experimental time, minimum temperature inside close type system decreased below -50°C . On this result, a unique characteristic of temperature distributions can be observed, it

increases according to the length direction of vaporizer, and this was reported by Choi and Chang in 1999^[5] and they could not to find why it was happened. However it can be certified through T_{11} as end point temperature of vaporizer-tube is lowest of all temperature of vaporizer surface in Fig. 7 and 8.

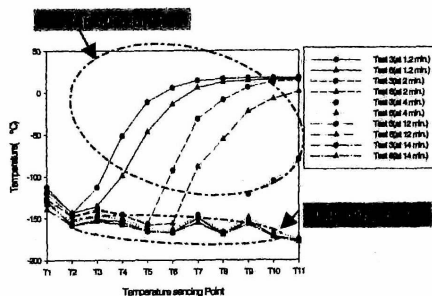


Figure 9: Temperature distributions of vaporizer surface in open ($v=6.93\text{m/s}$, $\dot{m}_{\text{LN}_2}=1.34\text{kg/min}$) and close ($v=6.93\text{m/s}$, $\dot{m}_{\text{LN}_2}=1.42\text{kg/min}$) system along the time and length direction.

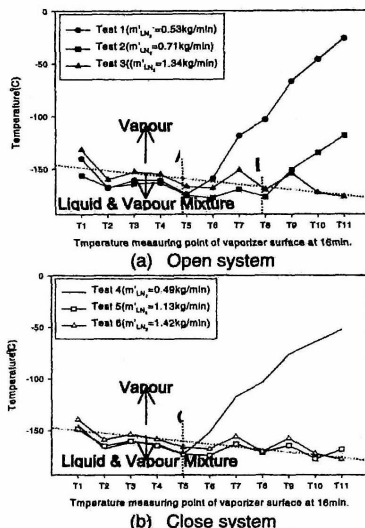


Figure 10: Temperature distributions of open and close system according to temperature measuring point on vaporization with flow rate variation at 16min.

Increasing and decreasing temperature on vaporizer surface of both open (test 3) and close (test 6) system was shown in Fig. 9. As shown by Fig. 9, temperature distributions according to length direction of vaporizer tube were observed similarly all in case test 3 and test 4. As time progress, region of increasing temperature is smaller and region of

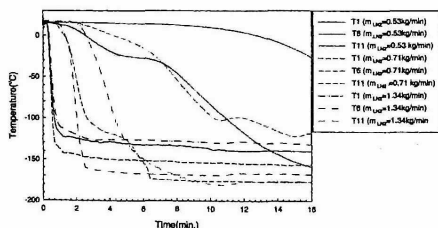
decreasing temperature is larger. This means that vapor region (superheated region) is increased due to cooling vaporizer. In other word, the saturated region is increasing. Initial pressure of LN₂ Tank was about 8.6bar and initial outlet pressure of vaporizer is atmosphere pressure (1.013bar). Therefore, decreasing temperature along length direction of vaporizer is due to the pressure. Specially, region of decreasing temperature by pressure drop is only presented at the saturated region, and increasing temperature by pressure drop is appeared at superheated region such as p-h diagram of Fig. 6. Also alteration of decreasing and increasing of temperature along length direction was guessed as the effects of the pressure pulsation. Shock wave and vaporization such mixing fluid and vapor inside vaporizer can be generated when the compressible fluid is a subsonic turbulent flow.^[7]

A(test 1), B(test 2), C(test4) of Fig 10 mean the changing position from saturated region to superheated region. That is as following:

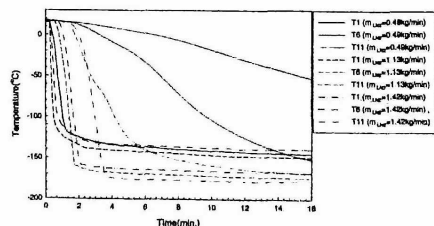
- Test 1 : after T₅(1,000mm) → vapor
- Test 2 : after T₆(1,600mm) → vapor
- Test 4 : after T₅(1,000mm) → vapor

Rest test 3, 5 and 6 was not completely vaporized due to high flow rate.

4.2 Temperature distributions on the vaporizer surface according to flow rate of liquefied nitrogen



(a) Open type system



(b) Close type system

Figure 11: Temperature distributions of vaporizer surface by $\dot{m}_{LN_2}$ variations in open and close system at $v = 6.93\text{m/s}$.

Fig. 11(a) shows the temperature distribution with respect to flow rates of liquefied nitrogen for open type system. And Fig. 11(b) is close type system. In fact, many of temperature positions on vaporizer surface were measured in experiment. But, Fig. 11 shows only T₁, T₆ and T₁₁. T₁ is inlet of vaporizer surface, T₆ is middle position and T₁₁ is outlet. When flow rates of liquefied nitrogen are increasing, temperature of surface increases and reaches steady state more quickly.

Observing temperature at same position on the vaporizer surface according to the variation of flow rates, test 2 ($\dot{m}_{LN_2} = 0.71\text{kg/min}$) is lower than test 1 ($\dot{m}_{LN_2} = 0.53\text{kg/min}$), and test 2 is lower than test 3 ($\dot{m}_{LN_2} = 1.34\text{kg/min}$). In this manner, surface temperature of vaporizer is not decreased at steady state enough increasing of flow rate because of characteristics of liquefied nitrogen which has turbulent flow by vaporizing. In case of test 3 ($\dot{m}_{LN_2} = 1.34\text{kg/min}$) surface temperature value before steady state was $T_1 > T_6 > T_{11}$ but surface temperature value after steady state was $T_1 > T_{11} > T_6$. As mentioned above, the unique phenomenon admits of no other explanation in the present experiment. Temperature distributions in Fig. 11(b) are close type system and similar to Fig 11(a).

4.3 Temperature distributions on open and close system by air velocity variation

Fig. 12 shows the temperature distribution of open system according to variation of the air velocity at $\dot{m}_{LN_2} = 0.76\text{m/s}$ and Fig.13 is about close system at $\dot{m}_{LN_2} = 0.80\text{m/s}$. The flow rate of liquefied nitrogen must be same but this experiment never be keep it on. That is because the valve of tank was controlled manually. Increasing of air velocity mean that heat flux is increased. So, surface temperature of vaporizer was increased due to increasing air velocity and heat transfer at vaporizer was promoted. This can be certified by Fig. 12 and 13. Also, the open system was promoted heat transfer larger than the close system because the air of ambient is flowed into the system. Additionally, in case close system, temperature inside chamber decreased below -64°C , and heat exchanged air temperature before the chamber decreased to -90°C according to increasing of air velocity because of recycling of cooling air.

Fig 14 shows the average low quantity of heat for each test. Generally, Average loss quantity of heat increases by increasing of flow rate of liquefied nitrogen. Average loss quantity of heat does not have large difference because this experiment is accomplished for relatively short time. However, testing for long time will decrease loss quantity of heat inside close system because the temperature difference will gradually decrease by recycling of air inside system. Accordingly, representing such as concept like RT to average loss quantity of heat at air, 3.35RT in case test 3 was evaluated higher than others of tests.

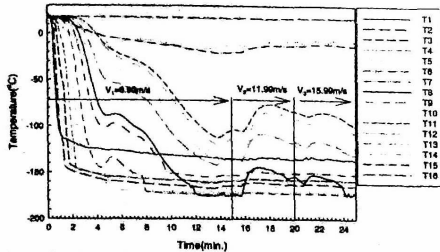


Figure 12: Temperature distributions by air velocity at $\dot{m}_{LN_2} = 0.76 \text{ kg/min}$ in open system.

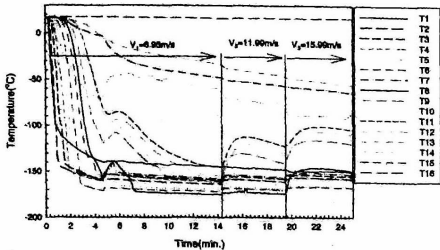


Figure 13: Temperature distributions by air velocity at $\dot{m}_{LN_2} = 0.80 \text{ kg/min}$ close system.

4.4 Loss quantity of heat at air inside system according to variation of flow rate of liquefied nitrogen.

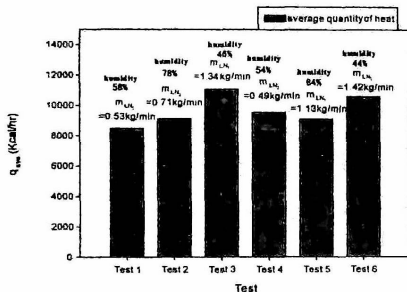


Figure 14: Average loss quantity of heat of open and close system by $\dot{m}_{LN_2}$ variation.

5. CONCLUSION

(1) The surface temperature of vaporizer was rapidly reached in steady state according to increasing of liquefied nitrogen flow rate. Layer of the freezing moisture was created thicker than the close system, and heat transfer on vaporizer was promoted because the increase of air velocity has increasing the temperature of vaporizer surface and exhausted nitrogen gas.

(2) The open type system is very useful to vaporize the liquefied nitrogen quickly. It is found that

test 3 ($\dot{m}_{LN_2} = 1.34 \text{ m/s}$) which was evaluated of 3.35RT

higher than others of tests. On the other side, the advantage of close type system is that this system can be obtained lower temperature, and air temperature before the chamber can be decreased down to -90°C according to increasing of velocity because of recycling of cooling air.

(3) During vaporization process of liquefied nitrogen, Temperature is decreased in saturated region (at $\Delta p < 0$), and is increased in subcooled region (at $\Delta p \leq 0$, $\Delta h > 0$) and superheated region (at $\Delta p \leq 0$, $\Delta h > (\Delta h)_{critical} > 0$), which was certified by p-h diagram. Also the transition point to vapour can be discovered through temperature distributions on vaporizer surface.

(4) Whole decreasing temperature is due to pressure drop and unique phenomenon of temperature fluctuation at vaporizer surface along the length direction was considered due to the effects by the pressure pulsation, shock wave and vaporization of compressible fluid.

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