Feasibility Study on Practical Application of AAV with a Defrosting Method

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***Abstract*—KOGAS (Korea Gas Corporation) has two types of vaporizer to regasify LNG (Liquefied Natural Gas), which are ORVs (Open Rack Vaporizers) and SCVs (Submerged Combustion Vaporizers). Recently, KOGAS has been undergoing difficulties to additionally construct ORVs and SCVs due to environmental issues. So, KOGAS is considering eco-friendly vaporizers, which have never been experienced in the past, not to use seawater. AAV (Ambient Air Vaporizer) is a strong candidate for a clean environment. Hence, this work is to investigate its possibility for LNG import terminals of KOGAS in South Korea. For practical application of AAV, a feasibility study was carried out with candidate vaporizers. KAAV (KOGAS-type Ambient Air Vaporizer) is revealed as more effective than other vaporizers.**

***Index Terms*—feasibility study, practical application, AAV, KAAV, defrosting method, LNG**

I. Introduction

ORVs (Open Rack Vaporizers) are used for base load and SCVs (Submerged Combustion Vaporizers) are done for peak shaving of NG (Natural Gas) and back-up facilities against thermal degradation of ORVs due to low seawater temperature during winter season. However these days, KOGAS has been undergoing difficulties to additionally construct ORVs due to environmental issues such as cold seawater effluent and residual chemical contents. So, KOGAS is considering eco-friendly vaporizers, which have never been experienced in the past, not to use seawater. AAV (Ambient Air Vaporizer) is a strong candidate for a clean environment. Thus, this work is to investigate its possibility in the temperate regions for LNG import terminals in South Korea.

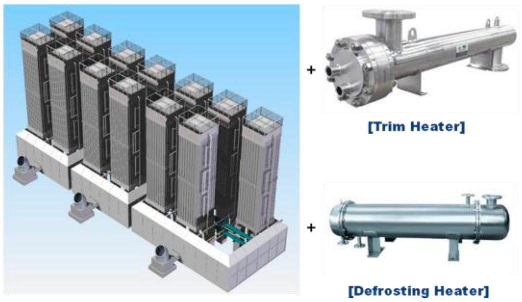

Figure 1. Composition of KOGAS-type AAV.

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KOGAS carried out a feasibility study of KAAV (KOGAS-type AAV), which is synthetically devised through real operation cases of AAV in LNG import and satellite terminals, for Inchon and new Jeju LNG import terminals. The KAAV, which is a combination of NAAVs (Natural-draft AAVs), fans, a trim heater and a defrosting heater, is shown in Fig. 1. The KAAV can minimize the number of cells for a defrosting process and control artificial fog as a risk factor. In the present, the frost growth and artificial fog are covered. Finally KAAV is compared with ORVs, SCVs and their combination.

II. Humid Air Dynamics

A. Frost Growth

Frost growth rate is a crucial factor to evaluate the feasibility of KAAV. It is investigated under Korean climate. Numerical simulations are performed on frost growth as thermal characteristics of KAAV. Saturation and supersaturation models of frost growth [1] are compared with boundary layer analysis under Korean climate. Table I shows non-dimensional boundary layer equations, which are momentum, energy, and concentration equations. The supersaturation model is physically more accurate than the saturation model because the saturation vapor pressure is less than the local vapor pressure, which the vapor is sub-cooled below its saturated state.

TABLE I. Non-Dimensional Boundary Layer Equations

Boundary layer	Equations	Boundary conditions
Momentum	$\zeta''' + 0.5\zeta\zeta'' = 0$	$\zeta(0)=0, \zeta'(0)=0, \zeta'(\infty)=1$
Energy	$\tau'' + 0.5\Pr\zeta\tau' = 0$	$\tau(0)=0, \tau(\infty)=1$
Concentration	$\xi_v'' + 0.5Sc\zeta\xi_v' = 0$	$\xi_v(0)=0, \xi_v(\infty)=1$

Fig. 2 and Fig. 3 show the solutions of the boundary layer with the supersaturation degree under the air temperature of -35°C and the wall temperature of -20°C at the relative humidity of 20%, 50%, and 80% in summer. Fig. 4 and Fig. 5 show the results under the above same conditions in winter. The supersaturation degree of the supersaturation model is linearly increased in the vicinity of thermal boundary layer. We can identify the decrease of the supersaturation degree related to the frost deposition and growth in winter. The frost formation on a cold surface is greatly declined because the absolute

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humidity of winter is much less than that of summer under the identical relative humidity. From the results, the surface temperature is identified as being below 0 °C.

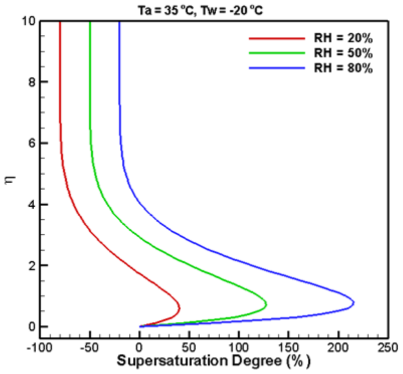

Figure 2. Solutions of a saturation model in summer.

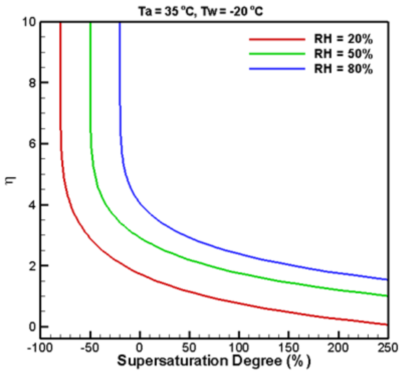

Figure 3. Solutions of a supersaturation model in summer.

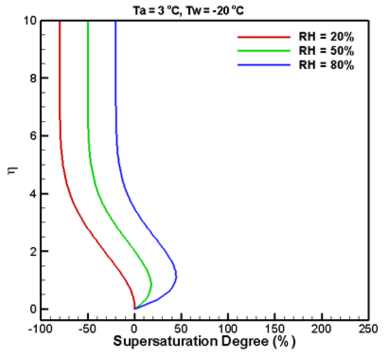

Figure 4. Solutions of a saturation model in winter.

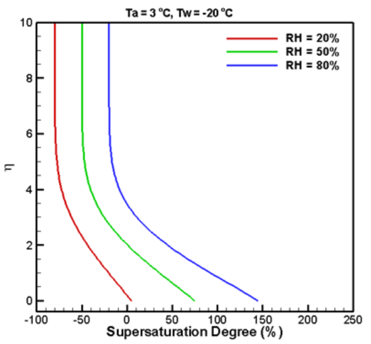

Figure 5. Solutions of a supersaturation model in winter.

KOGAS used the theoretical model of Cheng [2] to investigate the frost growth rate. Effects of plate surface temperature and air conditions, such as air velocity, temperature, and humidity ratio, on the frost growth rate can be evaluated by using this model. The growth rate of the frost thickness under the air conditions of the Inchon LNG import terminal can be found as

$$\frac{dx}{dt} = \frac{h_M (w_a - w_s)}{147.55x \exp(0.227T_s)(dT_s/dx) + \rho_f} \tag{1}$$

where dT_s/dx is the temperature gradient at frost surface. The gradient can be expressed as

$$k_f \frac{dT_s}{dx} = h(T_a - T_s) + \rho_f \frac{dx}{dt} \Delta h \tag{2}$$

Equations (1) and (2) are numerically solved with the bisection method by Burden & Faires [3].

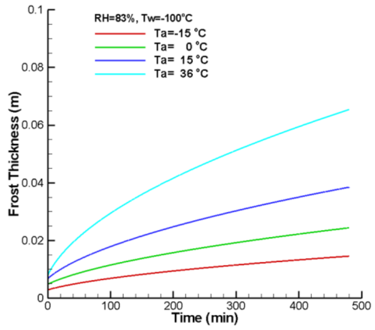

Figure 6. Frost growth with time.

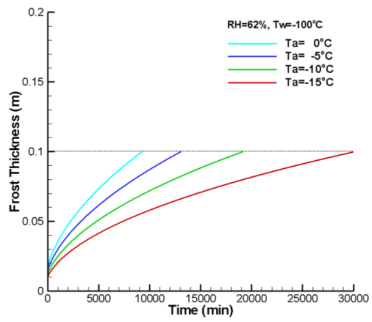

Figure 7. Frost growth with time.

Fig. 6 shows the frost growth with time under the relative humidity of 83%, the wall temperature of -100°C, and the air temperature of -15, 0, 15, and 36°C. The frost thickness is rapidly increased at the initial time, and then monotonously increased. Fig. 7 shows the maximum possible working time of KAAV with air temperature of below 0°C without any defrosting in winter. The maximum possible working time is increased with the decrease of air temperature at the corresponding relative humidity of 62% and the wall temperature of -100°C. We checked the possible working time until the frost thickness reaches 0.1m. The results can provide us with the information on the defrosting process in winter.

B. Artificial Fog Formation and Visibility

Artificial fog can be a disaster because it obstructs one's field of vision in the terminals. So the artificial fog should be certainly controlled. This work doesn't cover the fog control because the mechanism of fog formation and evaporation is complex. Herein, we describe only artificial fog formation and visibility.

To predict the artificial fog formation of KAAV, KOGAS used the equation of fog concentration proposed by Gavelli [4]. The equation becomes

$$F = \rho_m (w_m - w_s) \tag{3}$$

where ρ and ω denote density and absolute humidity. The subscripts of m and s mean mixture and saturation.

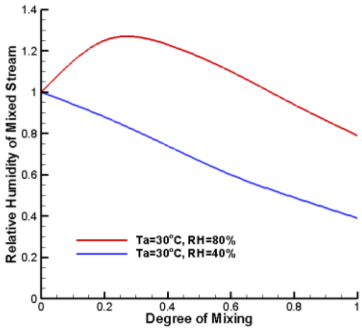

Figure 8. Relative humidity of mixed stream with DoM.

Fig. 8 shows the variation of relative humidity as a function of the DoM (Degree of Mixing) of the effluent and ambient air in the mixed air stream. The results are in a fairly good agreement with Gavelli's results. Fig. 9 shows a possible period of fog formation under averaged relative humidity of the Inchon terminal. The dense fog formation occurs from mid May through mid September. Also, a fog formation field is illustrated in Fig. 10 with air temperature and RH (Relative Humidity) at the DoM of 0.3.

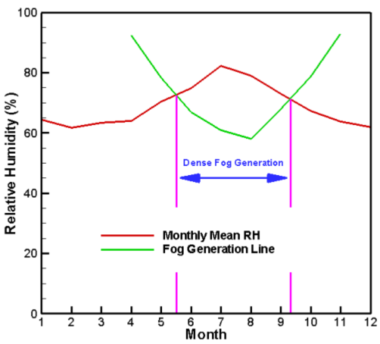

Figure 9. Fog formation with month.

The visibility of artificial fog can be expressed as

$$V = 24 f^{-0.65} \tag{4}$$

where f is the density of artificial fog. Equation (4) is propsed by Arnulf *et al*. [5]. Table II shows minimum visibility per month. RH means that Relative Humidity can generate artificial fog in the outlined month. MV denotes Minimum Visibility. MRH stands for Mean Relative Humidity at the Inchon terminal. KOGAS is considering minimizing the fog formation in the site because it can be a disaster. Although the visibility is not involved to the feasibility of KAAV, it is a crucial factor because any accident is not permitted in the LNG import terminals. Finally, KOGAS could find the possibility of KAAV in the side of performance and risk because the demand of NG is very low in summer.

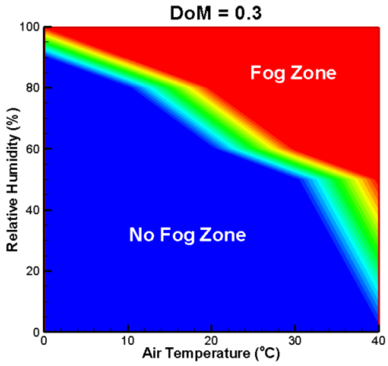

Figure 10. Fog formation field with air temperature and RH.

TABLE II. MINIMUM VISIBILITY WITH MONTH

Month	4	5	6	7	8	9	10	11
RH(%)	92	78	67	61	58	68	79	93
MV(m)	50	25	20	16	14	15	25	64
MRH(%)	64	70	**75**	**82**	**79**	**73**	67	64

III. ECOMOMIC EVALUATION

A. Economic Analysis

For specific facilities, we don't employ general economic analysis methods because we can't estimate profits. So we employ a total cost, which is expressed as the summation of all costs, to compare each vaporizer. We have two classes, which are two kinds of the total cost for base load and for full load. For the base load, the total cost leads to

$$f_{cost} = CC_0 + \sum_{i=1}^{n} (OC_i + EC_i) \tag{4}$$

where CC is a capital cost, OC denotes an operation cost, EC means environmental charges, and n indicates evaluation period. For the full load, an improved total cost [6] is employed. It can evaluate the penalty cost of stop cells and thermal degradations of ORVs. To evaluate the vaporizers more accurate, the improved total cost is considered as

$$f_{cost} = CC_0 + \sum_{i=1}^{n} (OC_i + OPC_i + EC_i) \tag{5}$$

where OPC (Opportunity Cost) is applied to stop vaporizers and lower send-out vaporizers as compared with full rated capacity. We use (4) to evaluate the base load of the Inchon terminal and (5) to do the full load of new Jeju terminal.

First of all, the three-types of candidate vaporizers are selected and compared for the terminals. KOGAS has enough knowledge and experience on the ORVs and SCVs. Although KOGAS has never had any experience on KAAVs, a considerable portion of this evaluation could be achieved by the help of manufacturers [7], [8] and reported documentations [9], [10].

B. Inchon LNG Import Terminal

KOGAS carried out the economic evaluation of KAAV for the Inchon terminal. The evaluation includes three cases, which are on for the air temperature of above 18°C, another for the seawater of above 5°C, and other for the Inchon terminal.

TABLE III. VAPORIZER RANKINGS FOR AMBIENT AIR OF ABOVE 18°C

Item		ORV	SCV	KAAV
Land usage	[m²/ton]	11.7	6.3	29.3
Capital cost	[KK$/ton]	133.4	56.1	163.7
Operation cost	[KK$/ton.yr]	5.2	128.7	0.5
EC	[KK$/ton.yr]	1.6	8.1	-
Total cost(25yrs)	[KK$/ton]	301.1	3,475.4	176.6
Rank		2nd	3rd	1st

TABLE IV. VAPORIZER RANKINGS FOR SEAWATER OF ABOVE 5°C

Item		ORV	SCV	KAAV
Land usage	[m²/ton]	11.7	6.3	29.3
Capital cost	[KK$/ton]	133.4	56.1	163.7
Operation cost	[KK$/ton.yr]	5.2	128.7	10.9
EC	[KK$/ton.yr]	1.6	8.1	0.7
Total cost(25yrs)	[KK$/ton]	301.1	3,475.4	455.7
Rank		1st	3rd	2nd

TABLE V. VAPORIZER RANKINGS FOR THE INCHON TERMINAL

Item		ORV+SCV	SCV	KAAV
Land usage	[m²/ton]	15.9	6.3	29.3
Capital cost	[KK$/ton]	170.8	56.1	163.7
Operation cost	[KK$/ton.yr]	18.3	128.7	13.1
EC	[KK$/ton.yr]	2.4	8.1	0.7
Total cost(25yrs)	[KK$/ton]	687.1	3,475.4	509.5
Rank		2nd	3rd	1st

Table III shows the vaporizer rankings for the ambient air temperature of 18°C. The top priority is KAAV, with ORV and SCV following. Table IV shows the vaporizer rankings for the seawater temperature of above 5°C. KAAV needs the operation of a trim heater and a defrosting heater below the air temperature of 18°C, whereas ORV doesn't need the operation of any back-up and auxiliary facilities. So the top priority becomes ORV. Table V shows the vaporizer rankings for the Inchon terminal. ORV needs a back-up facility, which is SCV. The top priority is revealed as being the KAAV. The last order is SCV. Although SCV is using a small land and the lowest capital cost, the total cost is the highest because of the highest operation cost.

C. New Jeju LNG Import Terminal

For economic evaluation of new Jeju LNG import terminal, the NG pattern is assumed to be a harmonic function with respect to TDR (Turn Down Ratio), which is a ratio of peak to valley of NG demand, and t (time) as follows

$$NG_t = A_{send-out}\left[1-(TDR-1)/TDR_{\max}\sin(2\pi ft)\right] \tag{6}$$

where A denotes a peak send-out, f is a frequency, a value of 0.04167, t indicates a time in month, and TDR_{max} is reported as 10 in KOGAS. The monthly demand pattern and air temperature are illustrated in Fig. 11.

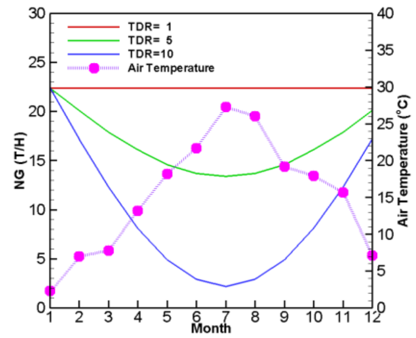

Figure 11. NG demand pattern and air temperature with month

TABLE VI. VAPORIZER RANKINGS FOR JEJU LNG IMPORT TERMINAL

Item		ORV	SCV	KAAV
Land usage	[m²/ton]	11.7	6.3	29.3
Capital cost	[KK$/ton]	133.4	56.1	163.7
Operation cost	[KK$/ton.yr]	2.6	55.0	9.2
EC	[KK$/ton.yr]	8.5	3.6	10.5
Total cost(25yrs)	[KK$/ton]	724.2	1,608.3	695.7
Rank		2nd	3rd	1st

A comparison of targeted vaporizers for the Jeju terminal is shown in Table VI assumed as the peak send-out of 22.4 T/H. The ORV and SCV are considered as small-scaled vaporizers. From the results, if ORV doesn't have environmental problems, ORV can be more effective than other vaporizers. However, KAAV is suitable for the new Jeju LNG import terminal because it doesn't have any environmental issues.

IV. CONCLUSIONS

KOGAS investigated the feasibility to introduce eco-friendly vaporizers for the LNG import terminals in South Korea. Although all situations aren't considered, the KOGAS-type AAV is revealed as being economically and environmentally superior to other vaporizers and their combinations.

Consequently, KOGAS could find the possibility of KAAV to be applied to the Inchon and future Jeju LNG import terminals. A further study will carry out a thorough inspection of KAAV on a defrosting process and artificial fog control.

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