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A Study of Liquid Nitrogen Inert Gas System for LNGC Diesel Engine Crank Chamber

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LNGC 디젤기관 크랭크 챔버용 액체질소 불활성가스 시스템에 관한 연구

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Abstract : *It is necessary to install the inert gas system(IGS) for preventing fire and explosion in LNGC main diesel engine crankcase besides oil mist detector(OMD) unit with CO_2 gas injector. Therefore, to design the liquid nitrogen IGS, analytical work is conducted for predicting the heat input load of liquid nitrogen heater with two-phase stratified flow model. This paper also presents the effects of changes in pipe diameter, saturated pressure, and inclination angle by ship's movement on cryogenic two-phase stratified flows. It is found that the stratified model gives reasonable predictions, and the model is effective to predict the heat input load of liquid nitrogen IGS.*

Key Words : *Inert Gas System(IGS), LNGC, Cryogenic Fluid, Liquid Nitrogen, Two-Phase Stratified Flow*

요 약 : LNGC 주기관의 크랭크 챔버 내 유증기 폭발 방지를 위해 기존의 이산화탄소 가스인젝터가 부착된 오일미스트 감지기 외에 불활성가스 시스템을 설치할 필요가 있다. 특히, LNGC 선박은 액체질소를 손쉽게 확보할 수 있는 장점이 있기 때문에 액체질소를 이용한 불활성가스 시스템을 도입하기 위한 설계 기초 단계로서 해석적 연구를 시행하였다. 또한 액체질소 최소 소모량 시스템을 개발하기 위하여 층상류 모델을 적용하였으며, 층상류 흐름에 미치는 유로관경, 포화압력과 선박동요에 따른 배관 기울기 등의 영향에 대해서도 조사하였다. 또한 질소와 같은 극저온 유체들과 여기에 사용된 예측 모델과의 비교 검토를 통하여 극저온 유체에 대해서도 모델의 유효성을 검증하였으며, 액체질소 불활성가스 시스템의 액체질소를 가스로 상변환 시키는데 소요되는 가열기의 열부하도 예측할 수 있었다.

핵심용어 : 불활성가스 시스템, *LNG* 운반선, 극저온 유체, 액체질소, 이상층상류

1. Introduction

Nitrogen gas(GN2) is the most common naturally occurring gas, which is also used as inert gas for preventing the formation of flammable mixtures in fuel and cargo tanks onboard airplane or ship.

Recently in most airplanes, onboard inert gas generation system(OBIGGS) generating nitrogen-enriched air(NEA) was installed to prevent fuel tank explosion accidents(Abramowitz and Boris, 1996; Summer, 2003).

Nitrogen generators with air separation process, similar to the OBIGGS in airplane were also operated onboard ships. In particular, LNG Carriers(LNGC) produce nitrogen gas by operating nitrogen generators for purposes, namely, for inerting and purging the cargo tank insulation, hold spaces and pipelines(Witherby Seamanship International, 2011).

The fire and explosion in LNGC main diesel engine crank chamber could be caused by oily mixtures with oxygen contacting a hot bearing or by a scavenge fire heating the dividing plate between the scavenge space and crankcase. However, only oil mist detector(OMD) unit with CO_2 gas injector is bolted to the main diesel engine crankcase door without inerting gas system(IGS). Therefore, this work was conducted to design the IGS capable of the control of temperature, pressure and oxygen concentration inside LNGC engine crank chamber. IGS for LNGC considered in here will

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use cryogenic liquid nitrogen(LN2) as inerting fluid due to the control of both temperature and pressure in crank chamber, and due to the benefit easily acquirable in hand from LNG terminals.

A key point to design the cost-efficient liquid nitrogen IGS is to predict the heat input load corresponding to generating the amount of inerting gas required to avoid the flammable range in crank chamber. The heat input load is minimized at low liquid nitrogen flow rate occurring cryogenic two-phase stratified flow.

Therefore, as the first step to design the liquid nitrogen IGS for LNGC, the analytical predictive results for the heat input load is calculated by using two-phase stratified flow model. And this paper also includes the effects of changes in pipe diameter, pressure, and inclination angle by ship's movement on two-phase stratified flows, and the prediction results are also compared with the cryogenic data.

2. Prediction model

Fig. 1 shows the design description of liquid nitrogen inert gas system(IGS) to prevent fire and explosion accidents in LNGC diesel engine crank chamber. This system will be composed of the liquid nitrogen(LN2) cylinder, the saturated pressure controller of LN2, the heater for vaporizing saturated liquid nitrogen into saturated nitrogen gas, the superheater to control both of temperature and pressure of inert gas in the crank chamber, and the orifice for low inert gas flow rate.

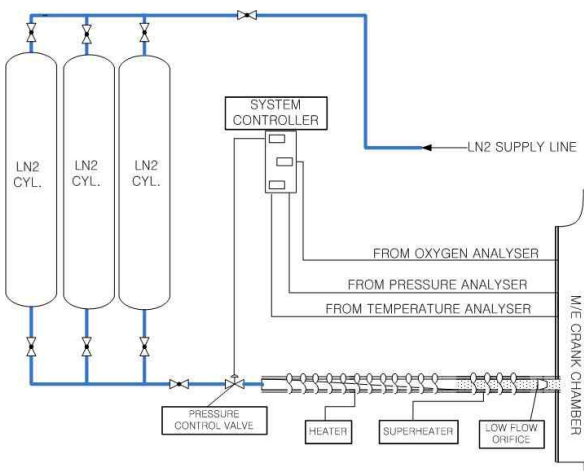

Fig. 1. Description of liquid nitrogen IGS for LNGC.

Generally, at low LN2 flow rate, cryogenic two-phase stratified flow also occurs in circular tube, similar to ordinary two-phase flow such as air-water and steam-water(JSME, 1989). At low LN2 flow rate, if liquid nitrogen single phase flows in the tube wall heated by heater attached to the IGS, the flow will also accomplish the phase change from liquid to vapor in the flow direction, simultaneously with change in thermal equilibrium quality from x=o to x=1. With further adding heat to the tube wall by superheater, saturated vapor single phase flow will be reached at superheated gas state and then flow into LNGC main engine crank chamber for playing the role of inerting gas.

And the required heater input load $H(w)$ in the range from quality x=o to x=1 can be calculated:

$$H=\dot{m}_g x h_g+\dot{m}_l(1-x)h_l \tag{1}$$

The equation (1) can be also reformed as:

$$\begin{aligned} H&=(\rho_g A_g u_g)xh_g+(\rho_l A_l u_l)(1-x)h_l \\ &=\left[\left(\frac{A_g}{A}\rho_g u_g\right)xh_g+\left(\frac{A_l}{A}\rho_l u_l\right)(1-x)h_l\right]A \\ &=\left[\alpha\rho_g u_g xh_g+(1-\alpha)\rho_l u_l(1-x)h_l\right]A \\ &=\left[\rho_g U_{gs}xh_g+\rho_l U_{gl}(1-x)h_l\right]A \end{aligned} \tag{2}$$

In order to predict the required heat input load(H), it is necessary to find out U_{gs}, U_{ls} to be able to exist at the stratified flow regime. Superficial gas velocity U_{gs} can be obtained from dimensionless form in the criterion for stratified flow occurrence condition as following(Taitel and Dukler, 1976):

$$F^2\left[\left(\frac{\tilde{u}_g}{1-\tilde{h}_l}\right)^2\frac{\sqrt{1-\left(2\tilde{h}_l-1\right)^2}}{\tilde{A}_g}\right]\geq 1 \tag{3}$$

where F is a Froude number modified by the density and pipe inclination angle.

$$F=\sqrt{\frac{\rho_g}{(\rho_l-\rho_g)}}\frac{U_{gs}}{\sqrt{Dg\cos\theta}} \tag{4}$$

And the dimensionless liquid level, $\tilde{h}_l$ can be expressed as:

$$\tilde{h}_l=\frac{h_l}{D} \tag{5}$$

where h_l is liquid phase level and the other dimensionless parameters are defined as:

$$\widetilde{A}_g = 0.25\left[\cos^{-1}\left(2\widetilde{h}_l - 1\right) - \left(2\widetilde{h}_l - 1\right)\sqrt{1-\left(2\widetilde{h}_l - 1\right)^2}\right]$$

$$\widetilde{A}_l = 0.25\left[\left(2\widetilde{h}_l - 1\right)\sqrt{1-\left(2\widetilde{h}_l - 1\right)^2}\right] + 0.25\left[\pi - \cos^{-1}\left(2\widetilde{h}_l - 1\right)\right] \quad (6)$$

$$\widetilde{u}_g = 1 + \frac{\widetilde{A}_l}{\widetilde{A}_g}$$

Consequently, superficial gas velocity, U_{gs} can be calculated by using equations (3)~(6).

And liquid superficial velocity, U_{ls} can be also predicted from following equation(Taitel and Dukler, 1976):

$$U_{ls} = \left\{\frac{\dfrac{C_g(\rho_g)^{1-m}\left(U_{gs}\widetilde{u}_g\right)^{2-m}}{2}\left(\dfrac{D\widetilde{D}_g}{\mu_g}\right)^{-m}}{\left(\widetilde{u}_l\right)^{2-n}\left(\widetilde{S}_l/\widetilde{A}_l\right)\left[C_l\left(\dfrac{D\widetilde{D}_l}{\mu_l}\right)^{-n}(\rho_l)^{1-n}\right]}\right\}^{\frac{1}{2-n}} \times \left\{\frac{\left[\dfrac{\widetilde{S}_g}{\widetilde{A}_g} + f_r\left(\dfrac{\widetilde{S}_i}{\widetilde{A}_l} + \dfrac{\widetilde{S}_i}{\widetilde{A}_g}\right)\right]}{\left(\widetilde{u}_l\right)^{2-n}\left(\widetilde{S}_l/\widetilde{A}_l\right)\left[C_l\left(\dfrac{D\widetilde{D}_l}{\mu_l}\right)^{-n}(\rho_l)^{1-n}\right]}\right\}^{\frac{1}{2-n}} + \left\{\frac{Dg\left((\rho_l-\rho_g)/\rho_l\right)\cos\theta}{\left(\widetilde{u}_l\right)^{2-n}\left(\widetilde{S}_l/\widetilde{A}_l\right)\left[C_l\left(\dfrac{D\widetilde{D}_l}{\mu_l}\right)^{-n}(\rho_l)^{1-n}\right]}\right\}^{\frac{1}{2-n}} \quad (7)$$

where $C=16$, $n=m=1$ for laminar flow, $C=0.046$, $n=m=0.25$ for turbulent flow, and the other dimensionless parameters are defined as:

$$\widetilde{S}_l = \pi - \cos^{-1}\left(2\widetilde{h}_l - 1\right),\ \widetilde{S}_g = \cos^{-1}\left(2\widetilde{h}_l - 1\right),\ \widetilde{S}_i = \sqrt{1-\left(2\widetilde{h}_l - 1\right)^2}$$

$$\widetilde{D}_g = \frac{4\widetilde{A}_g}{\widetilde{S}_g + \widetilde{S}_i},\ \widetilde{D}_g = \frac{4\widetilde{A}_l}{\widetilde{S}_l},\ \widetilde{u}_l = 1 + \frac{\widetilde{A}_g}{\widetilde{A}_l} \quad (8)$$

3. Discussion and validation

3.1 Discussion

As described in previous, superficial gas and liquid velocities U_{gs}, U_{ls} can be calculated by using stratified flow model, in order to predict the heat input load for IGS onboard LNGC. However, the ranges of U_{gs}, U_{ls} generating two-phase stratified flows can be strongly changed by various parameters such as pipe diameter, inclination angle by ship's movement, saturated pressure and, thermal properties of cryogenic fluids as like liquid nitrogen, hydrogen and helium.

Fig. 2 shows the prediction results for two-phase stratified flow existence condition for cryogenic fluid helium and nitrogen, and also for the ordinary fluid nitrogen-water and steam-water. The curves in the figure are obtained by using equations (3)~(8) with pipe inner diameter D=10 mm, saturated pressure P=1.2 bar and upward inclination angle from horizontal $\Theta=0.1^0$. Steam-water prediction curve lies in the more wide range than the other fluids.

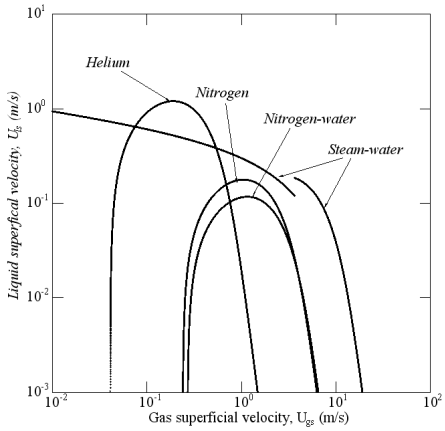

Fig. 2. Differences in two-phase stratified flow occurrence conditions between cryogenic and ordinary flows.

The cryogenic helium curve is similar to the cryogenic nitrogen and nitrogen-water curves but shifted low region of U_{gs} and high region of U_{ls}. And the cryogenic nitrogen curve is shifted toward the slightly higher U_{ls} than nitrogen-water. It is due to the large differences in density and viscosity between cryogenics fluids and ordinary fluids.

The effect of changes in pipe diameter on nitrogen two-phase stratified flow existence condition at P=1.2 bar and $\Theta=0.1^0$ is shown in the Fig. 3. A key result is the fact that the peak of dome-shaped curve is shifted toward lower U_{gs} and U_{ls}, with decreasing pipe diameter. In cases of D=10mm and D=20mm, the both gas and liquid flow are all turbulent whereas in the case of D=5mm, the stratified flow is divided to two regions, namely, one is laminar gas-laminar liquid at low U_{gs}, and the other is turbulent gas-laminar liquid at high U_{gs}.

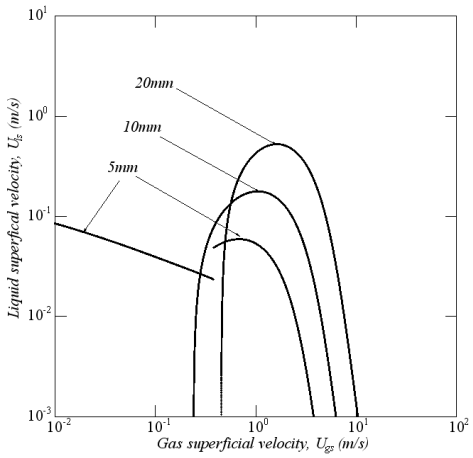

Fig. 3. Effects of diameter on cryogenic nitrogen two-phase stratified flow occurrence condition.

Fig. 4 shows the effect of pipe inclination angle on nitrogen two-phase stratified flow existence condition at D=10 mm and P=1.2 bar. The figure shows that the nitrogen two-phase stratified flow is strongly influenced by pipe inclination angle. As the pipe inclination angle slightly increases from horizontal to upward $\Theta=0.5^0$, the region of nitrogen stratified flow rapidly decreases and will disappear with a few degrees higher than $\Theta=0.5^0$.

However, as the pipe inclination angle increases from horizontal to downward, the nitrogen stratified flow region is gradually expanded. It will be due to the significant gravity effect on the gas-liquid two phase flow in inclination pipes. It is also found that the effect of inclination angle on the nitrogen stratified flow is more significant than that of diameter.

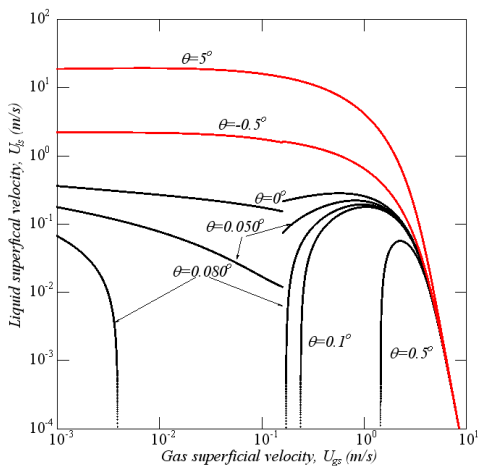

Fig. 4. Effects of pipe inclination angle on cryogenic nitrogen two-phase stratified flow occurrence condition.

Fig. 5 shows the effect of saturated pressure on nitrogen two-phase stratified flow existence condition at D=10 mm, P=1.2 bar and $\Theta=0.1^0$. The curve peak shifts toward left side of the map, as saturated pressure increases. And laminar gas-laminar liquid region reappears at p=0.5 bar. It is considered that the stratified flow is difficult to persist the stratified flow under increased pressure.

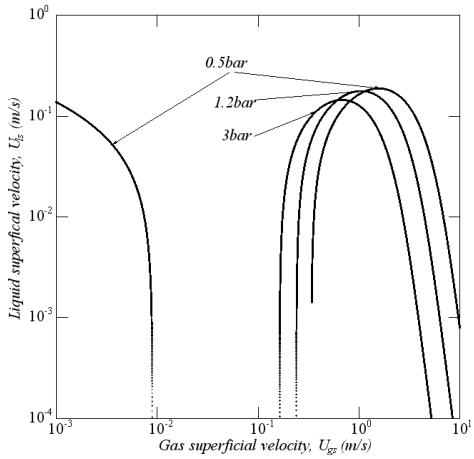

Fig. 5. Effects of saturated pressure on cryogenic nitrogen two-phase stratified flow occurrence condition.

3.2 Validation

Fig. 6 and Fig. 7 show the results compared stratified flow prediction model with previous experimental cryogenic hydrogen and nitrogen data(Van, 2001). These data are obtained from experiments with pipe diameter D=8.74 mm, upward inclination angle $\Theta=1.5^0$ from horizontal. Fig. 6 shows that only hydrogen stratified flow data place within the region predicted by this model, but four point data, namely, the other flow data exist beyond the predicted region.

Fig. 7 shows that all four nitrogen stratified flow data are perfectly inside the predicted region, except one point of the other flow data.

Fig. 8 shows the comparisons between this model and nitrogen-water stratified flow experimental data with D=10 mm, horizontal flow with inclination angle $\Theta=0^0$(Nakazawa, 1995). All of nitrogen-water stratified flow data exist in the predicted region, it shows reasonable predictions.

From comparisons between this prediction model and cryogenic stratified flow data, this prediction model give reasonable predictions. And it is also validated that this prediction model can be applied to cryogenic fluids.

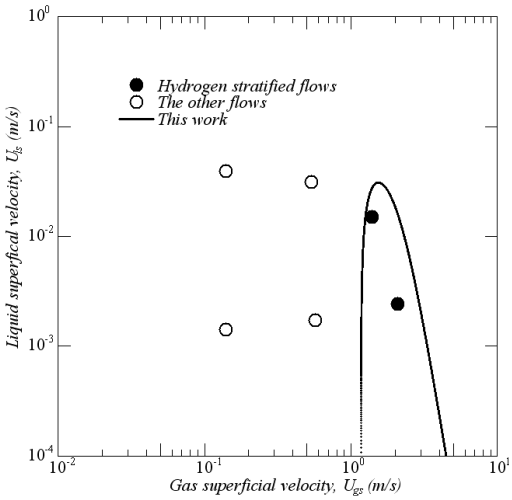

Fig. 6. Comparison between two-phase stratified flow prediction model and cryogenic hydrogen data.

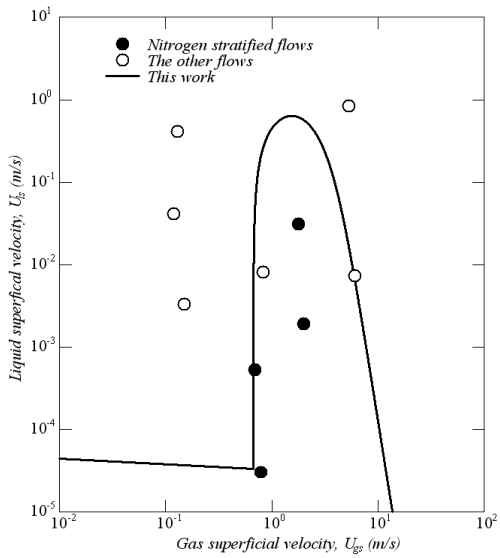

Fig. 7. Comparison between two-phase stratified flow prediction model and cryogenic nitrogen data.

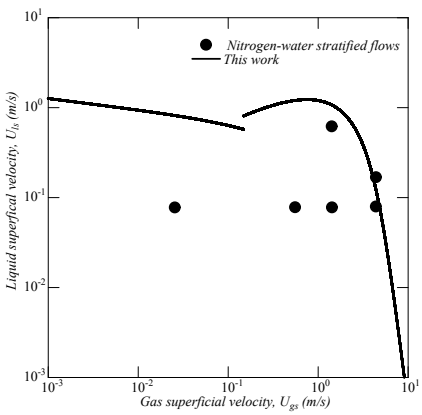

Fig. 8. Comparison between two-phase stratified flow prediction model and nitrogen-water data.

4. Heat input load

The heat input load of heater section in liquid nitrogen IGS onboard LNGC can be predicted form equation(2) with the values of U_{gs} and U_{ls} calculated by this stratified prediction model validated with various experimental data.

Fig. 9 shows the electric heat input load predicted at the conditions of the pipe diameter D=10 mm and upward inclination angle $\Theta=0.1^0$. As known from the figure, electric heat input load gradually increases with elevating saturated pressure for quality x<0.015, but decreases with elevating saturated pressure for 0.015<x<0.35. This implies that stratified flow quickly disappear with increasing the saturated pressure. And the maximum heat input load at 0.5 bar indicates approximately 1kw.

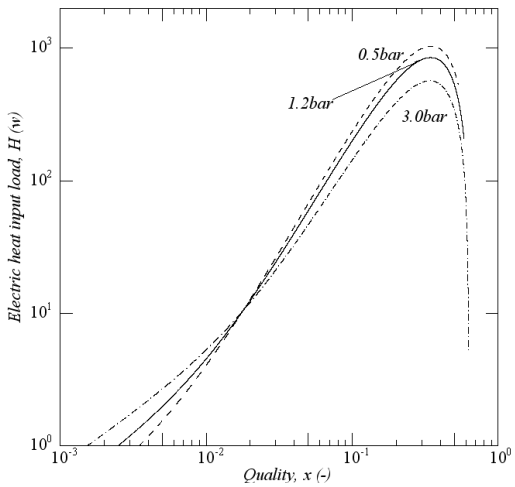

Fig. 9. Electric heat input load prediction of LN2 IGS with the change in saturated pressure.

Fig. 10 shows the electric heat input load predicted at conditions of the saturated pressure P=1.2 bar and upward inclination angle $\Theta=0.1^0$. The peak point of the heat input load increases, as the diameter size is larger. In the case of D=20 mm, the peak point places at x=0.34, the maximum heat input load is approximately 10 kw.

Fig. 11 shows the effects of pipe inclination angle on electric heat input load at pipe diameter D=10 mm and saturated pressure P=1.2 bar conditions. This figure indicates that the pipe inclines slightly upward form horizontal, the peak point of heat input load moves toward low quality x.

In downward stratified flow, although the inclination angle increases, the peak point of heat input load occurs at nearly constant x=0.68. In the figure, it is shown that the downward flow stratified flow can be happened in more widely liquid

flow rate range than upward flow.

Consequently, in the prediction of the heat input load of liquid nitrogen IGS, it is found that the inclination angle is the most important design parameter relatively to the pipe diameter or the saturated pressure.

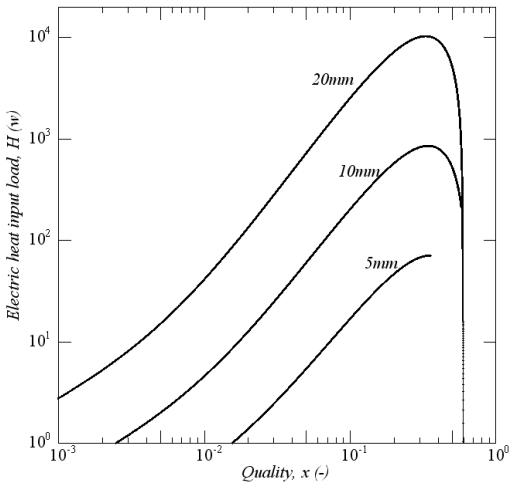

Fig. 10. Electric heat input load prediction of LN2 IGS with the change in pipe diameter.

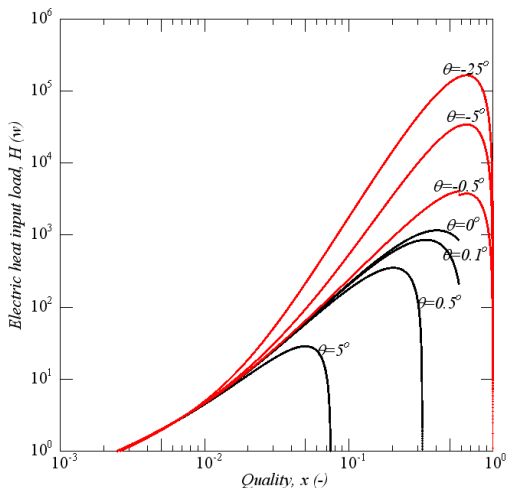

Fig. 11. Electric heat input load prediction of LN2 IGS with the change in pipe inclination angle.

5. Conclusion

As basic step to design the cryogenic liquid nitrogen inert gas system for LNG Carriers, analytical work was carried out. A key points in this work is to confirm the validation of stratified flow model with cryogenic fluids, and to predict the heat input load in heating section of inerting gas system, Therefore, the effects of various parameters on stratified prediction model were investigated. The summary of main results obtained in this work:

1. Stratified flow prediction model is strongly influenced by the pipe inclination angle relatively to pipe diameter, saturated pressure.
2. Stratified flow exists in more wide range at downward flow than at upward flow.
3. Comparisons between this prediction model and cryogenic stratified flow data presents very good agreement, and it was also validated that the prediction model was applicable to cryogenic fluids.
4. In the heat input load prediction of liquid nitrogen IGS, inclination angle is the most important design parameter.

Notation

A: total pipe cross-sectional area, $[m^2]$
A_g: gas phase pipe cross-sectional area, $[m^2]$
A_l: liquid phase pipe cross-sectional area, $[m^2]$
$\tilde{A}$: dimensionless pipe cross-sectional area, $[-]$
D: pipe diameter, $[mm]$
$\tilde{D}$: dimensionless pipe diameter, $[-]$
F: dimensionless Froude number, $[-]$
g: acceleration of gravity, $[m/s^2]$
H: Electric heat input load, $[kW]$
h: specific enthalpy, $[kJ/kg℃]$
h_l: liquid phase level, $[mm]$
h_l: dimensionless liquid phase level, $[-]$
$\dot{m}$: mass flow rate, $[kg/s]$
P: saturated pressure, $[bar]$
$\tilde{S}$: dimensionless wetted perimeter, $[-]$
$\tilde{S}_i$: dimensionless gas-liquid interface length, $[-]$
U_{gs}: superficial gas velocity, $[m/s]$
U_{ls}: liquid velocity, $[m/s]$
u_g: real gas velocity, $[m/s]$
u_l: real liquid velocity, $[m/s]$
x: thermal equilibrium quality, $[-]$

Greek letters
α: void fraction, $[-]$
θ: pipe inclination angle, $[^o]$
ρ: density, $[kg/m^3]$

Subscripts
g: gas phase
l: liquid phase.

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