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◉ 論 文

A Study on Unsteady Temperature Distribution Analysis of Moss Type LNG Carrier by Insulation System

Jin-Goo Kim* · Yong-Mo Kim** · Chun-Sik Kim***

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MOSS형 LNG선의 방열구조에 의한 비정상 온도분포해석에 관한 연구

김 진 구* · 김 용 모** · 김 춘 식***

Key Words : LNG(액화천연가스), BOG(증발가스), Cooling down(예냉), Insulation(방열), Steady state(정상상태), Thermal stress(열응력), Temperature distribution(온도분포)

요 약

본 연구는 Moss형 LNG선박의 방열구조에서 LNG탱크에 침입하는 열량과 선체의 온도분포를 예측하고, 운항 중 LNG탱크를 Cooling down(예냉)하는 경우 발생하는 비정상상태에서 LNG탱크에 발생하는 국부적인 열응력을 검토할 수 있는 비정상 온도분포해석과 LNG증발량을 검토하였다. 특히 운항 중인 선박을 대상으로 일반적인 수치계산시에 필요한 각종 입력절차를 간소화 하고 경계조건 선정시에 비 전문가도 쉽게 이용할 수 있는 전산프로그램을 개발하였다. Moss형 LNG탱크의 예냉작업에 필요한 최적의 냉매량과 예냉조건을 비정상상태에서 해석한 것은 설계자 및 선박 운항자에게 유용하게 이용될 것이다.

1. Introduction

The pollution of atmospheric environment is coming serious and it is understood that the cause of green house effect is enormous increase of CO_2 gas by using fossil fuel. So we can estimate the law will oblige us to use natural gas.

The inner part of the tank of LNG carrier is maintained -162℃, because liquified temperature of LNG is -162℃ under atmospheric pressure. If this cargo leaks, fire, explosion and low temperature brittleness of hull will occur and enormous damage will be attend. So special technique and carefulness is necessary in drawing and building[1)~4)]. Especially, insulation of LNG carrier is the most important technique

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* Graduate of Korea Maritime University
** Korea Heat and Fluid Co., Ltd
*** Korea Maritime University

with structure analysis, welding and assembling.

That cargo is isolated from heat purposes to compress BOR under economical loss and prevent hull to be dropped under limit temperature. Analysis of heat stress, which occurs in tank by ultra low temperature LNG, is point in drawing LNG carrier. Normally, to prevent heat stress of skirt when cargo is loaded, precooling is carried out before loading, that is to say, Cool down. This has to be done quickly and has not to consume much refrigerant. Considering these, to find the best fitted method, it is needed to know the connection by deduction among spray amount, spray nozzle arrangement and heat stress accompanied by tank cooling velocity.

In this study, we model MRV type LNG carrier and examinate how insulation system and insulator affect to hull temperature distribution, and develope CAD program to calculate the BOR at that moment. We theoretically find out temperature distribution of spherical tank and skirt on cool down process under unsteady state. Analysis method and result are under.

2. Analysis model and method under steady state

2.1 Analysis model and heat conductivity of every material

Fig.1 shows hull structure model and structure of skirt. Concerning heat transfer between hull and atmosphere of sea water, Jacoff equation[5]

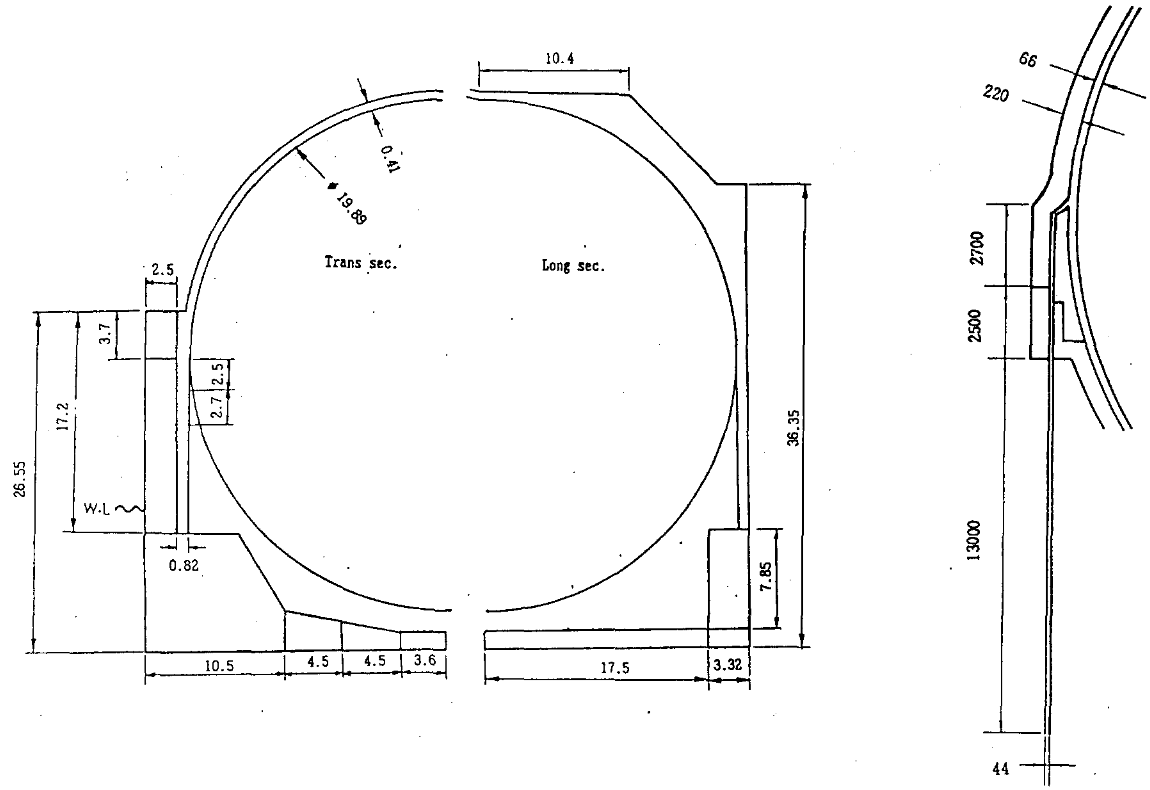

Fig. 1 Calculation Model of Hull

(1) is used for vertical plate, Mcadams's equation[6] (2) is used for flat plate, and in case of natural convection, Colburn equation[5] (3) is used for forced convection.

$$N_u = 0.13(G_r \cdot P_r)^{\frac{1}{3}} \quad (1)$$

$$N_u = 0.14(G_r \cdot P_r)^{\frac{1}{3}} \quad (2)$$

$$N_u = 0.036\ R_e^{0.86} \cdot P_r^{\frac{1}{3}} \quad (3)$$

Where,

$$N_u = \frac{hL}{k},\ G_r = \frac{\beta g(T_w - T_\infty)L^3}{\nu^2},$$

$$P_r = \frac{C_p \mu}{k},\ R_e = \frac{VL}{\nu}$$

N_u=Nusselt Number, G_r=Grashof Number

P_r=Prandtl Number,

R_e=Reynolds Number

β : Volume Expansion Coefficient (1/℃)

g : Acceleration of Gravity (m/s)

ν : Coefficient of Kinematic Viscosity (m^2/s)

C_p : Specific Heat at Constant Pressure (J/kg℃)

μ : Coefficient of Viscosity (N · s/m^2)

k : Heat Conductivity (W/mh℃)

h : Convective Heat Transfer Coefficient (W/m^{2}h℃)

V : Fluid Velocity (m/s)

L : Length (m)

T_u : Wall Temperature (℃)

T_∞ : Fluid Temperature (℃)

2.2 Analysis method

The Hull is considered 2-dimensional steady state without internal heat generation, this type of differential equation can be applied

$$\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right) = 0 \quad (4)$$

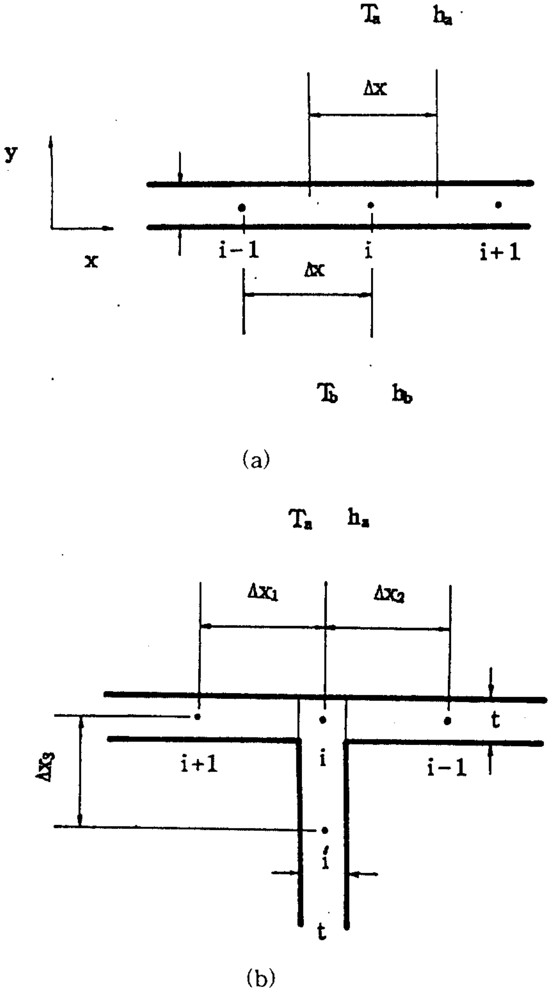

Fig. 2 Control Volume at Hull

In Fig.2 (a) shows grid point arrangement of control volume of vertical and flat plate, (b) shows grid point arrangement of control volume of T shaped part of hull. Assume that heat conductivity k is constant at all grid point and temperature of every point dominate in control volume. Like (a) in Fig.2, change heat flux of y direction by conduction in eq.(1) to heat flux by convection and apply energy equilibrium equation to point i.

(heat capacity from i+1 and i-1 to control volume by conduction)
+ (heat capacity from a and b to control volume by convection) = 0 (5)

Influx heat capacity from i+1 and i-1 to i by conduction is expressed as eq.(6) and eq.(7). Influx heat capacity to i by convection is expressed as eq.(8) and eq.(9).

$$q_{i+1\to i}=\frac{k\cdot t(T_{i+1}-T_i)}{\Delta x} \tag{6}$$

$$q_{i-1\to i}=\frac{k\cdot t(T_{i-1}-T_i)}{\Delta x} \tag{7}$$

$$q_{a\to 1}=h_a\Delta x(T_a-T_i) \tag{8}$$

$$q_{b\to 1}=h_b\cdot\Delta x(T_b-T_i) \tag{9}$$

Total heat capacity in control volume is 0 because it is steady state. Adjust above equations, temperature at i (Ti) is shown as

$$T_i=\frac{\frac{k\cdot t}{\Delta x}(T_{i+1}-T_{i-1})+h_a\cdot\Delta x\cdot T_a+h_b\cdot\Delta x\cdot T_b}{2\frac{k\cdot t}{\Delta x}+h_a\cdot\Delta x+h_b\cdot\Delta x} \tag{10}$$

Same way, apply energy balance to (b) in Fig2, Ti yields

$$T_i=\frac{\frac{k\cdot t}{\Delta x_1}(T_{i+1}-T_{i-1})+\frac{k\cdot t}{\Delta x_3}T_i+h_a\cdot\Delta x_2\cdot T_a}{2\frac{k\cdot t}{\Delta x_1}+k\cdot t\frac{\quad}{\Delta x_3}+h_a\cdot\Delta x_2} \tag{11}$$

As shown in Fig.3, apply energy balance to control volume of skirt which insulator is attached on both side. Heat flux by conduction from i +1 and i-1 to i is equal to eq.(6) and eq.(7) and heat flux by convection from a and b to i is

$$q_{a\to i}=\lambda_a\cdot\Delta x(T_a-T_i) \tag{12}$$

$$q_{b\to i}=\lambda_b\cdot\Delta x(T_b-T_i) \tag{13}$$

$$\lambda_a=\frac{1}{\frac{1}{h_a}+\frac{1}{\frac{k_1}{t_1}}}=\frac{h_a\cdot k_1}{h_a t_1+k_1}$$

$$\lambda_b=\frac{h_b\cdot k_1}{h_b t_1+k_1}$$

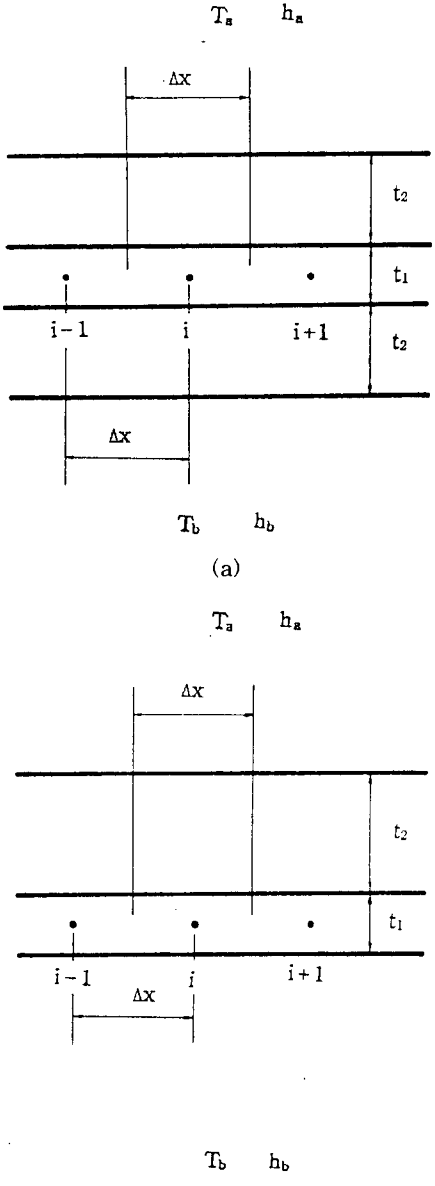

Fig.3 Control Volume at Skirt

Ti, temperature at point i is expressed as

$$T_i = \frac{\frac{k \cdot t}{\Delta x}(T_{i+1} + T_{i-1}) + \lambda_a \cdot \Delta x \cdot T_a + \lambda_b \cdot \Delta x \cdot T_b}{2\frac{k \cdot t}{\Delta x} + \lambda_a \cdot \Delta x + \lambda_b \cdot \Delta x} \tag{14}$$

Heat flux by conduction from i+1 and i−1 to i at skirt and spherical plate which insulator is attached on one side is expressed as eq.(6) and eq.(7) and heat flux by convection from a to i is expressed as eq.(12) and heat flux by convection from b to i is expressed as eq.(8). So Ti temperature of skirt and spherical plate at i is expressed as

$$T_i = \frac{\frac{k \cdot t}{\Delta x}(T_{i+1} + T_{i-1}) + \lambda_a \cdot \Delta x \cdot T_a + h_b \cdot \Delta x \cdot T_b}{2\frac{k \cdot t}{\Delta x} + \lambda_a \cdot \Delta x + h_b \cdot \Delta x} \tag{15}$$

And skirt consist of Al alloy, SUS 304 and high tensile steel, therefore harmonic average is used for boundary plate constructed by different materials.

2.3 Calculation of temperature distribution and BOR

Table 1 Property of Insulation Material

	SG on spherical surface	Sphere and skirt panels
Density(kg/m^3)	30.0	25.5
Tensile strength (kg/m^2)	2.6	2.5
Compressive strength(kg/m^2)	3.0	1.5
Coefficient of thermal contraction (1/ °C)	10 x 10^{-5}	3.8 x 10^{-5}
Thermal conductivity (kcal/mh °C)	0.030	0.030

Table 1 is physical property used in this study. In calculating temperature distribution of hull, we first calculate convective heat transfer coefficient h to calculate heat flux by convection as shown in Fig.2. Natural convection heat transfer coefficient h is the function of Grashof number, but the Grashof number is connected with temperature of wall which fluid is contact with. So, first, temperature distribution of hull of wall have to be calculated to calculate hull temperature distribution. Because thickness of hull is relatively thin, it does not matter putting that there is no temperature slope accompanied by hull thickness t at the part which insulator is not attached to, and temperature of wall which fluid is contact with is equal to temperature in control volume. But we have to calculate temperature of insulator surface is insulator is attached. Contact resistance occurs at insulator attached plate but disregarded in this calculation. Finite difference equation is used to calculate hull, skirt and spherical surface temperature, and temperature distribution on surface of insulator is calculated by sum of heat flux by convection from contact fluid to surface of insulator, and heat flux by conduction from surface insulator to control volume. Temperature distribution at every hold is calculated by sum of heat capacity flowed in every hold.

Put the heat capacity invaded from north hemisphere is Q_{NP}, the heat capacity invaded from south hemisphere is Q_{SP} and the heat capacity invaded from skirt is Q_{SK}.

Therefore total invaded heat capacity yields

$$Q_T = Q_{NP} + Q_{SP} + Q_{SK} \tag{16}$$

and BOR is expressed as

$$BOR = (24 \cdot Q_T / V \cdot \gamma \cdot \rho) \times 100 \tag{17}$$

V: Tank Volume (m^3)
γ : Latent Heat of Vaporization (kcal/kg)
ρ : Specific Weight (kg/m^3)

2.4 Result of analysis and consideration

Fig.4 shows the result of analysis of hull temperature distribution of 98% cargo loaded operation, in the case of atmosphere temperature is -18℃, wind velocity is 5 knot, sea water temperature is 0℃, assumed insulator thickness is 220mm and material is polystyrene. To prevent the invasion of radiation heat and protect insulator from damage, insulator shelter is established. It shows hull temperature distribution when sea water is not loaded in ballast tank.

The hull is contact with sea water, we can assume that hull is heated by atmosphere. But at vertical section, tank is connected with next tank and before the tanks bulk head lies. So we can assume that it is isothermal state. Therefore temperature distribution at each section are shown relatively low because heat invasion is impossible from vertical section. Table 2 shows

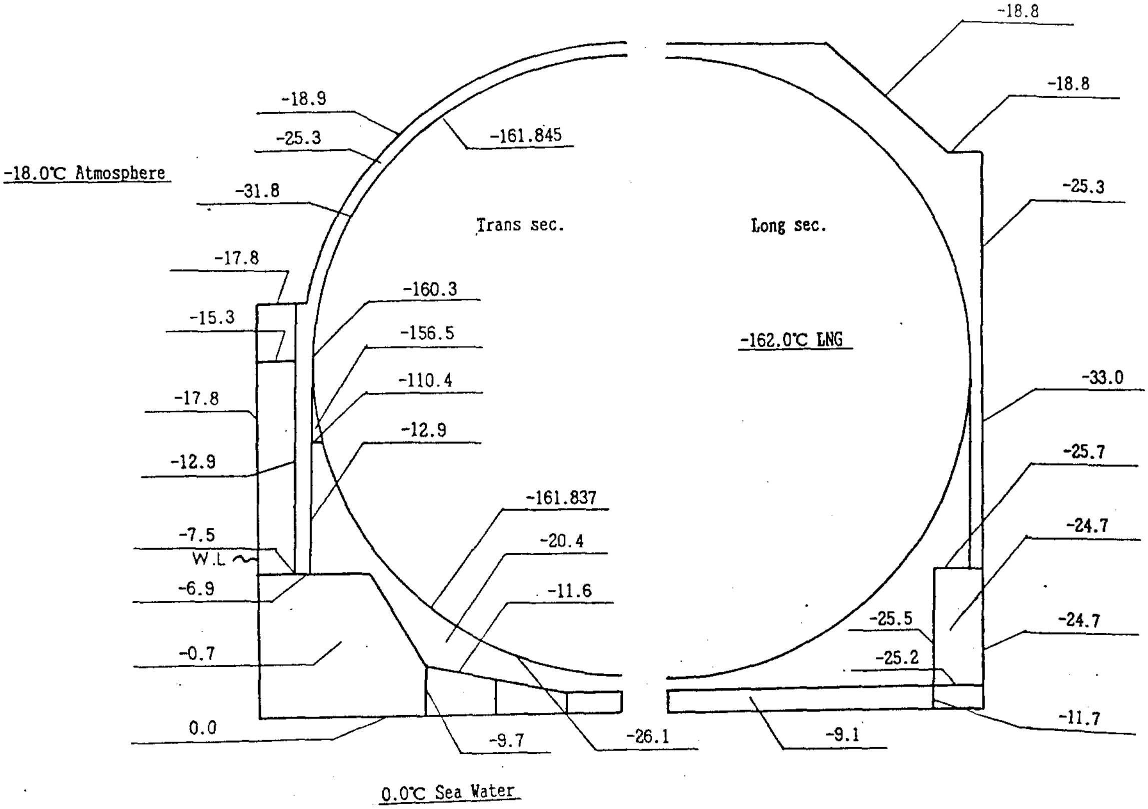

Fig.4 Calculation Results of Hull Temperature Distribution

Table 2 Calculation Results of Invasion heat and BOR

Atmosphere Condition (℃)	North		South		Skirt		Total	
	Invasion Heat	BOR	Invasion Heat	BOR	Invasion Heat	BOR	Invasion Heat	BOR
Atm. Temp. -18 Sea Temp 0	53.15 kw/h	0.0613 %/day	39.96 kw/h	0.0461 %/day	8.45 kw/h	0.0097 %/day	101.50 kw/h	0.1171 %/day
Atm. Temp. 45 Sea Temp 32	72.51 kw/h	0.0836 %/day	49.28 kw/h	0.0568 %/day	10.63 kw/h	0.0123 %/day	132.40 kw/h	0.1527 %/day

calculation result at this moment. We know from table. 2, BOR is 11.9% and invasion heat is 101.5kw in case atmosphere temperature is -18℃ and sea water is 0℃, and in case atmosphere temperature is 45℃ and sea water is 32℃, BOR is 15.3% and invasion heat is 132.4kw.

Fig.5 is representing the effect of atmosphere and sea water to BOR. BOR rises according to sea water and atmosphere temperature rises. BOR is affected more by sea water than atmosphere. The reason of this is because, in spite of small contact area, heat transfer coefficient of sea water is larger than that of air. the reason of relatively small affection is hull is constructed doubly and double bottom tank itself rolls as insulator, but upper part of tank which is contact with atmosphere is constructed only by insulator shelter. So the effect of sea water is not greater than we expected.

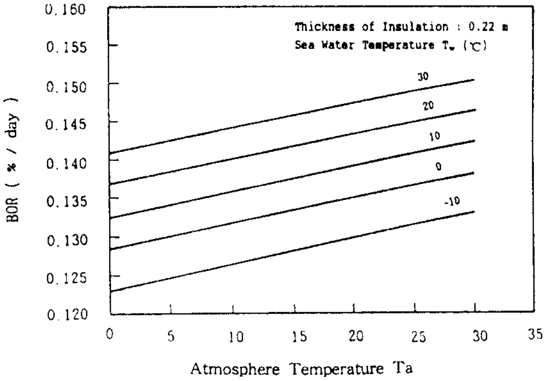

Fig.5 BOR Variation according to Sea Condition

Fig.6 shows the effect of thickness of insulator to BOR. Operated in case atmosphere temperature is 45℃ and sea water is 32℃ with 250mm insulator, BOR is 14%. 2% is reduced than that of 220mm insulator. This result is calculated without loading in ballast tank. So if loaded in ballast, we can estimate rising of BOR and hull temperature. Generally, insulator is thicker and thicker, BOR is thinner and thinner. But the degree does not go exactly with growing thickness. For example, we think that BOR will be reduced by 50%, if insulator is thick by 2 times i. e. 0.12m to 0.24m, but this calculation shows only 56% reduction. It is because heat invasion is not reduced from skirt in spite of increasing insulator. So we have to diverse a scheme to keep off the invasion from skirt to reduce BOR effectivity.

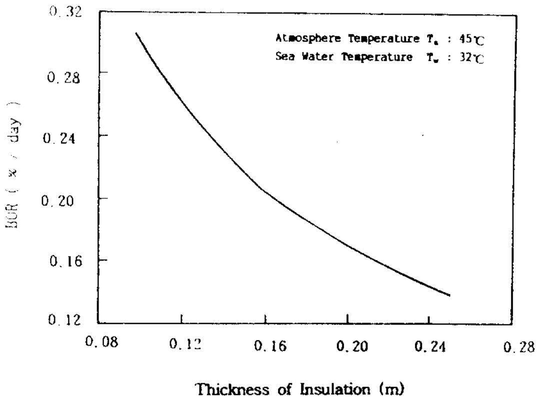

Fig.6 BOR according to Thickness of Insulation

3. Temperature profile in tank on precooling

3.1 Analysis model and method

Generally, environmental temperature of inner part of tank is lowered at upper part of pipe tower and that bring about natural convection, and heat is exchanged, and cooling occurs.

To obtain the temperature variation in a tank under unsteady state condition, we assume that tank is convergence mass system, and temperature is regular, and calculate temperature assuming that heat equilibrium is attained by heat exchange between sprayed refrigerant and gas, and considering the effect of heat taken away from tank by evaporation of refrigerant and invaded heat from skirt and insulator. Here, it is not necessary to consider density change in heat transfer in solid. So it is shown as

$$\rho c\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}(\lambda\frac{\partial T}{\partial x}) + S \tag{18}$$

T is temperature, ρ is density, c is specific heat, λ is heat transfer coefficient, S_h is heat generation rate per unit volume.

To derive the discretization equation, assume that ρc is constant and put time step is △t, control volume is △x, and integrate the eq.(18) and divided by △t.

$$\frac{\rho c}{\Delta t}\int_w^e\int_t^{t+\delta t}\frac{\partial T}{\partial t}dtdx = \frac{1}{\Delta t}\int_t^{t+\delta t}\int_w^e\frac{\partial}{\partial x}(\lambda\frac{\partial T}{\partial x})dxdt + \frac{1}{\Delta t}\int_t^{t+\delta t}\int_w^e Sdxdt \tag{19}$$

Unsteady state term :

$$\frac{\rho c}{\Delta t}\int_w^e\int_t^{t+\delta t}\frac{\partial T}{\partial t}dtdx = \rho c\frac{\Delta V}{\Delta t}(\ T_P{}^n - \ T_P{}^o) \tag{20}$$

Conduction term :

$$\frac{1}{\Delta t}\int_t^{t+\delta t}\int_w^e\frac{\partial}{\partial x}(\lambda\frac{\partial T}{\partial x}\partial x)dxdt \tag{21}$$

$$= \frac{1}{\Delta t}\int_r^{r+\Delta t}\frac{\lambda_e(\ T_E - T_P)}{(\delta x)_e} - \frac{\lambda_w(\ T_P - T_W)}{(\delta x)_w}dt$$

$$= f_t\left\{\frac{\lambda_e(\ T_E - T_P)}{(\delta x)_e} - \frac{\lambda_w(\ T_P - T_W)}{(\delta x)_w}\right\}^n$$

$$+(1 - f_t)\left\{\frac{\lambda_e(\ T_E - T_P)}{(\delta x)_e} - \frac{\lambda_w(\ T_P - T_W)}{(\delta x)_w}\right\}^o$$

Generation term:

$$\frac{1}{\Delta t}\int_t^{t+\delta t}\int_w^e Sdxdt = f_t\ S^n + (1 - f_t)\ S^o\Delta V$$

$$= f_t\{\ S_c + \ S_P\cdot\ T_P\}^n \tag{22}$$

$$= (1 + f_t)\{\ S_c + \ S_P\cdot\ T_P\}^o\Delta V$$

Capital subscript P,E,W means neighbor grid points and grid point P of Dependent variable T, and small letter subscript e,w mean control-volume faces, and upper subscript o,n mean the value of t and t+ △t. It is variable of time and in this study we use fully implicit scheme ; f_t=1 arrange above eq.

$$a_P\ T_P = \ a_E\ T_E + \ a_W\ T_W + b \tag{23}$$

$$a_E = \frac{\lambda_e}{(\delta x)_e} \tag{24}$$

$$a_W = \frac{\lambda_w}{(\delta x)_w} \tag{25}$$

$$a_P{}^o = \frac{\rho c\Delta V}{\Delta t} \tag{26}$$

$$b = \ S_c\Delta V + \ a_P{}^o\ \ T_P{}^o \tag{27}$$

$$a_P = \ a_E + \ a_W + \ \ a_P{}^o - \ S_P\Delta V \tag{28}$$

It is shown as the form of simultaneous equation about T_p grid temperature we want to know. Thomas Algorithm is used to calculated.

3.2 Analysis result and consideration

Fig.7 shows temperature distribution at skirt when 18000kg refrigerant is sprayed per hour. Initial temperature is 30℃ that is equal to atmosphere temperature. Cross line is dimensionless length when we assume that skirt length is 1, and vertical line is temperature. Time step is 2 hours. Knowing from this Figure, in skirt, it takes 17 hours to cool down to 110℃ temperature that cargo loading is possible.

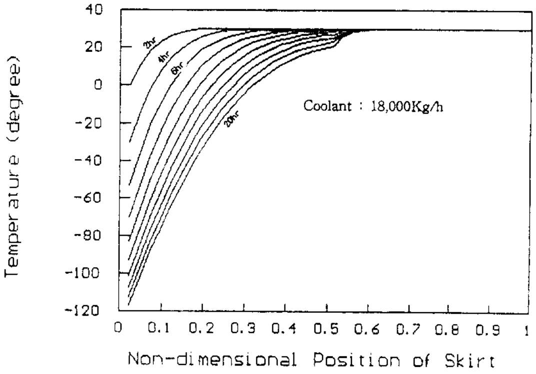

Fig.7 Temperature Distribution at Skirt under Unsteady State

Fig.8 shows vapour temperature variation in a tank at this moment. At initial state of precooling, temperature drops rapidly, but as time goes by, dropping rapidly comes slow. Especially, this is distinguished according as refrigerant amount rises.

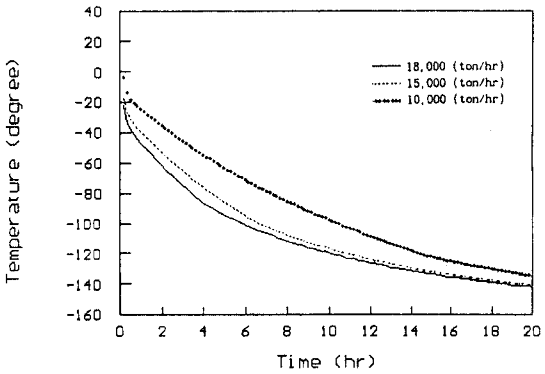

Fig.8 Vapor Temperature Variation in Tank

Knowing from Fig.9, according to temperature drop in the tank, sprayed refrigerant is not evaporated and remain in tank and falls cooling effect. In this case, spraying amount falls at the rate of not evaporated amount. If refrigerant amount rises, this also rises. Calculating this amount is very important to predict the characteristics of each thermal response on precooling and it is core technique of this study.

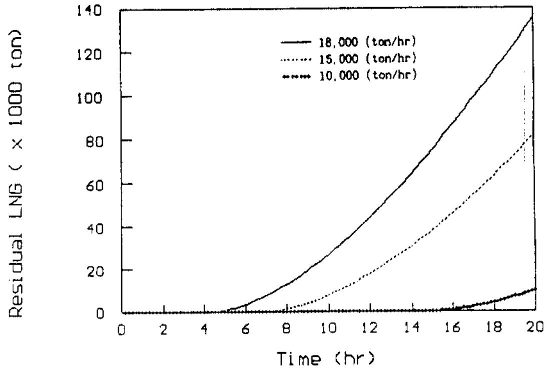

Fig.9 Residual LNG according to Cool down process

In this study, we calculated heat exchange between droplet and environment by direct method when droplet is sprayed.

Fig.10 shows temperature distribution of tank wall where refrigerant amount is 18000 kg and time step is 2 hours. Cross line is dimensionless position expressed by angle between north pole and the situation of tank when we put north pole is 0, thus south pole is π. 0.5 is equator and temperature is relatively higher than other part.

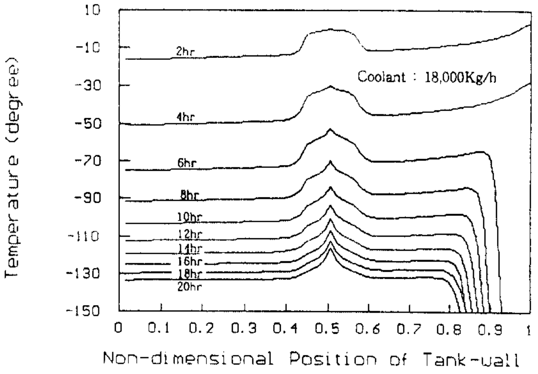

Fig.10 Temperature Distribution on Tank Surface

According to cooling, heat invade from skirt, which has relatively high temperature, to equator and raise wall temperature of equator. and if temperature rises more than certain degree compared to environment, heat stress concentrates and bring about collapse of skirt. With the passage of time, at the lower part of tank low temperature area, where temperature is near that of refrigerant, occurs. It is, as stated above, because not evaporated refrigerant get accumulated. If liquified refrigerant is piled up in tank, the temperature of lower part of thank rapidly drops.

4. Conclusion

In this study, we developed computer program to be put to practical use as source of carrier management technique improvement and stability estimation of hull by analysis of temperature distribution of every material which consist of LNG carrier.

To put together the result;

(1) We developed temperature distribution simulation program on precooling and hull temperature analysis program which can predict hull temperature distribution according to change of weather on voyage.

(2) If insulator thickness is thick, BOR drops, but drop-rate is not in proportion to insulator thickness in case of MOSS type LNG carrier.

(3) In MOSS type LNG carrier, BOR is 0.1525% when environment temperature is 45℃, sea water temperature is 32℃ and insulator is 22mm.

(4) Temperature rises rapidly from not insulated part of skirt.

(5) After precooling, according as environmental temperature drops, sprayed refrigerant which is not evaporated get accumulate on bottom of tank.

(6) Because there be heat invasion, temperature of equator is sustained relatively high compared to other part, so heat stress occurs at the connecting part between skirt and sphere.

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