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Heat Transfer and Evaporation Mathematical Model of LNG covered by High Expansion Foam

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Abstract

With the expanding of liquefied natural gas (LNG) usage, its security hidden trouble appeared gradually. For security reasons, small-scale experiment was carried out using LN_2 (whose thermal physical property parameters is similar to that of LNG, and do not affect the validity of the study) instead of LNG. Observing high expansion foam physical structure after it covering LN_2, we find out there's a three layer structure above the LN_2 at stable stage, the ice layer (including the tentacles below), freezing foam layer and the foam layer. Through observation and analysis, we build a physical structure model of the foam. A new method to calculate thin film thickness using expansion ratio is proposed, and a heat transfer and evaporation model between foam and LNG in the initial stage is established. Also we build a physical structure model of the ice, and establish a heat transfer and evaporation model between ice and LNG in stable stage. Combined with heat transfer between LNG, ground and cofferdam, the heat transfer and evaporation model of LNG covered with foam was developed eventually.

0. Introduce

With the rapid economic growth, the demand of energy source is more and more large. At the same time, due to the serious global environmental problems, the natural gas as an important green energy will increase its proportion of primary energy consumption in the future. In 2013, world primary energy consumption grew by 2.0%, up to 12.73 billion tons of oil equivalent. The consumption of fossil fuels (oil, natural gas, coal) reached 11.032 billion of oil equivalent, grew by 1.7%, accounted for 86.7% of the total primary energy consumption ,the natural gas reached

3.02 billion of oil equivalent ,accounted for23.7% of the energy consumption as showed in Fig.1. According to the regional primary energy consumption structure, the proportions of natural gas in the Middle East, Europe, North America, South America, Africa, Asia-Pacific were 49.1%、32.8%、30.1%、22.5%、27.5%、11.2%[1]. The International Energy Agency (IEA) reckons the global natural demand will increase by 2.2% in over the next 17 years as showed in Fig.2, reach $3.98\times1012m^3$ in 2019[2]. As a type of natural gas, the liquid natural gas (LNG) solved the problem that the natural gas is disadvantaged for the large storage, so that it is convenient for a large number of import and export. Liquefied natural gas (85%-95% methane) is natural gas that has converted into liquid form by super cooling to -162.2℃ at atmospheric pressure. When LNG escapes from its containment, it will boil and evaporate which results in flammable vapor cloud.The cold vapor has heavier density than air, so the LNG vapor will mix with the surrounding air and be dispersed downwind by the gravity. Fire or explosion will happen once ignition source exist nearby, also causing enormous losses.For safety, the well-known US standard NFPA 59A made by National Fire Protection Association and the standard 49CFR (Code of Federal Regulations) Part 193 made by United States Congress are widely adopted internationally as LNG storage site design standard, which requires to take corresponding measures to minimize the influence of LNG leakage[3]. The standard stipulates enterprises should predict the area of maximum impact (ground level concentration of the area is greater than 1/2LFL). Foam extinguishing plays an important role in the liquid fire and the research about the control of diffusion in the cryogenic liquid vapor cloud has got the attention of experts in this field. Mannan used high expansion foam (HEX) to accelerate the diffusion of LNG vapor cloud, which could reduce the size of the flammable vapor cloud[4]. Welker et al. also found the result, and the higher expansion rate of foam made LNG spread faster[5][6]. University Engineers Inc. examined the effect of expansion foam on vapor dispersion and found the vapor concentration could be reduced up to 80% during an LNG high boil-off period at a distance of one pool diameter of the spill[7]. Drake et al. Found that the evaporation rate was closely associated to expansion rate of foam[8]. G.J.Konzek et al. studied the action principle of the blanketing effect of expansion foam on LNG[9]. Ishii found that liquid nitrogen gas went through the foam ,its temperature could be heated to 0℃[10]. Takeno studied the ability of HEX to raise the temperature of vaporized cryogenic gas; it was concluded that approximately 92% of the heat held in the applied foam was transferred into vapor to increase the buoyancy in this specific test[11]. The high expansion foam is believed to quickly blanket on the top of LNG spillage pool and warm the LNG vapor to lower the vapor cloud density at the ground level due to raising vapor buoyancy and enhancing vapor dispersion,which can reduce the ground level concentration and probability of accident. Meanwhile as a result of the cover with foam, once fire or explosion happen, the fire spread to LNG liquid pool which can cause larger pool fire accident will be prevented. But some water (its heat transfer coefficient is greater than the air's) contents in the foam will accelerate heat transfer between LNG liquid and surrounding. Consequently, when the foam contacts with the cryogenic LNG liquid, the water of some foam is cooled down forming ice, which increases vaporization rate. Since the blocking effect of ice covering the LNG liquid and foam above ice absorbing some of the LNG vapor, the vaporization rate is reduced. So, it is necessary to research on heat transfer between HEX, LNG liquid and LNG vapor. Although previous work has confirmed that expansion foam represents one promising technique to control LNG vapor dispersion, it is still unclear about the influence of water freeze and foam freeze to heat transfer and evaporation rate after the foam contact with cryogenic LNG liquid. Meanwhile more studies are needed to fill the knowledge gaps and distinguish foam internal physical structure and the warm effect of LNG gas with the heat transfer. The objective of the present investigation is to experimentally determine the foam internal physical structure and LNG evaporation rate. Specifically, this study aimed to determine (1) the physical structure of HEX and ice layer; (2) the method of calculating the thickness of single bubble; (3) the heat transfer and evaporation mathematical model of LNG liquid pool covered by Hi-Ex foam

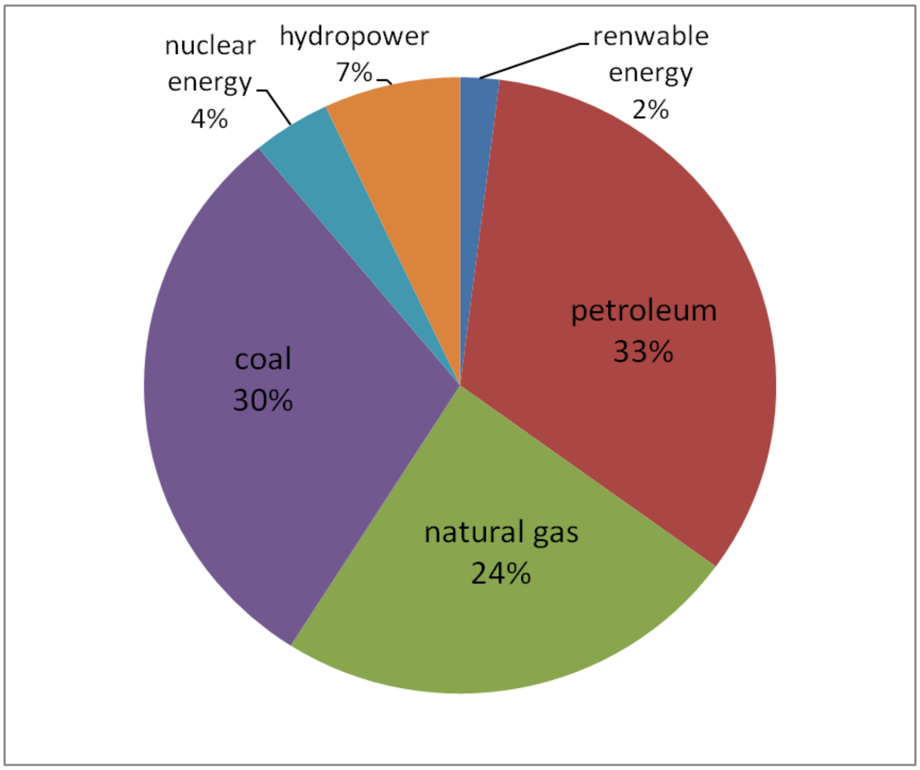

Fig.1 The composition of the global primary energy in 2013 (billion tons of oil equivalent)

	2015	2017	2019	Annual average growth
OECD America	923	955	968	0.8%
OECD Asia-Oceania	237	248	256	1.9%
OECD Europe	486	498	504	0.0%
Africa	132	145	159	5.0%
Non-OECD Asia(except China)	310	335	357	3.9%
China	213	263	315	11.3%

Former Soviet Union	675	676	681	0.0%
Latin America	171	186	204	3.8%
Middle East	456	495	535	3.9%
Total	3602	3800	3980	2.2%

Fig.2 Natural gas demand all over the world (10^9m^3)

1. Experimental setup

Due to the similarity of thermal physical parameter and in consideration of safety, the LNG was replaced by liquid nitrogen (LN_2) in the tests[11]. The inlet pressure and solution mixing ration of foam extinguishing agent used in experiments could be adjusted, which means the expansion ratio was controllable. The small scale field test was designed to spill LN_2 onto a stainless steel barrel container (the diameter is 39cm, the height is 35cm). A transparent box (the diameter is 39cm, the height is 120cm) made of resin glass was built for containing foam, which was convenient to observe the experimental phenomenon. The container has five thermal resistance sensors in a 2 cm interval embedded at five different depths, which were used to obverse the changes in LN_2 level. Six thermal resistance sensors in a 20 cm interval were mounted on the box and fence at different elevations to monitor temperature variation of foam. A measuring tape was applied on the side of the transparent box to record the changes of foam level during the experiments. The test container was placed on a scale with readability of 10g to monitor the mass loss rate of LN_2. All the measuring equipments were connected to a date acquisition system to record the experimental date for a systematic analysis. LNG was poured into the container until the level reached 10cm, the date acquisition system was applied at the same time. Then before applying the Hi-Ex foam, the transparent box was mounted on the container. The changes of foam level, foam temperature, LNG temperature were measured and still photos were taken. The experimental apparatuses are shown as Fig.3.

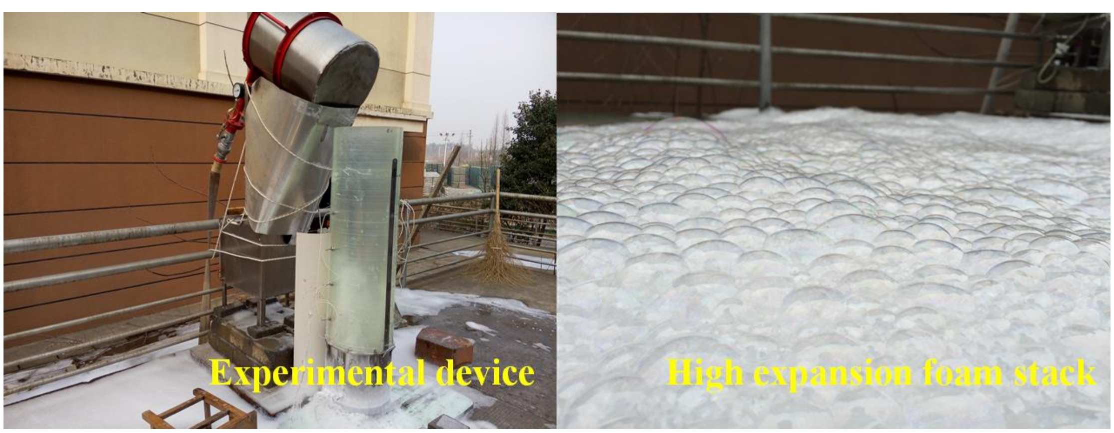

Fig.3 Field experimental device and high expansion foam stack

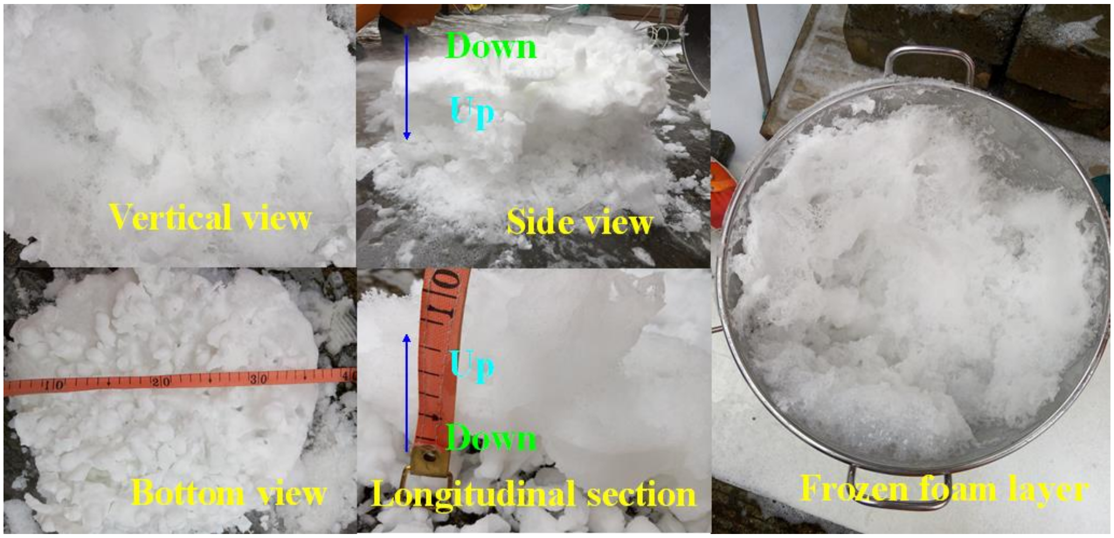

Fig.4 Three view drawing of the ice sample

After observating samples (as shown in Fig.3 and Fig.4), three layers including frozen ice layer, frozen Hi-Ex layer and soft layer of Hi-Ex foam were observed at the steady state as shown in Fig.5. The ice generated quickly and covered the surface of LN_2 after the Hi-Ex foam contacted with LN_2.

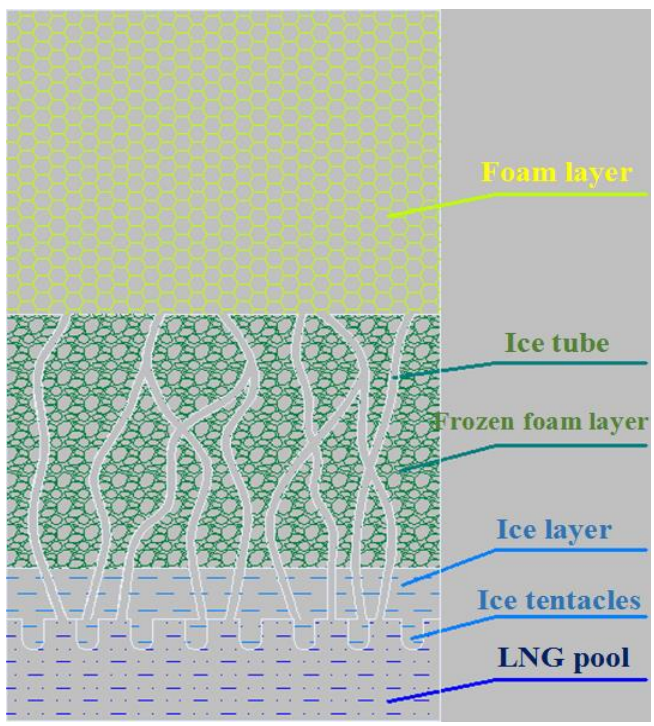

Fig.5 Multilayer structure of high expansion foam cover LNG

2.The physical structure of Hi-Ex foam and heat transfer model between foam and LNG

1.1 The physical structure of Hi-Ex foam

The test showed the geometric structure of the bubble approximated hexagonal prism as shown in Fig.3, and the upper surface and under surface were approximate to sphere. Considering the gravity of the internal air in the bubble, the bottom of single bubble was made up of downward raised spire and spheres of three directions as shown in Fig 6. By characterizing physical structure of the foam, formulas for calculating the surface of single bubble and method of counting film thickness through the foam expansion rate were deduced. Single bubble was composed of film and internal air. The bubbles were arranged closely at the same level, which constituted a foam layer as shown in Fig.7. The superposed foam layers made up a pile of foam as shown in Fig.7.

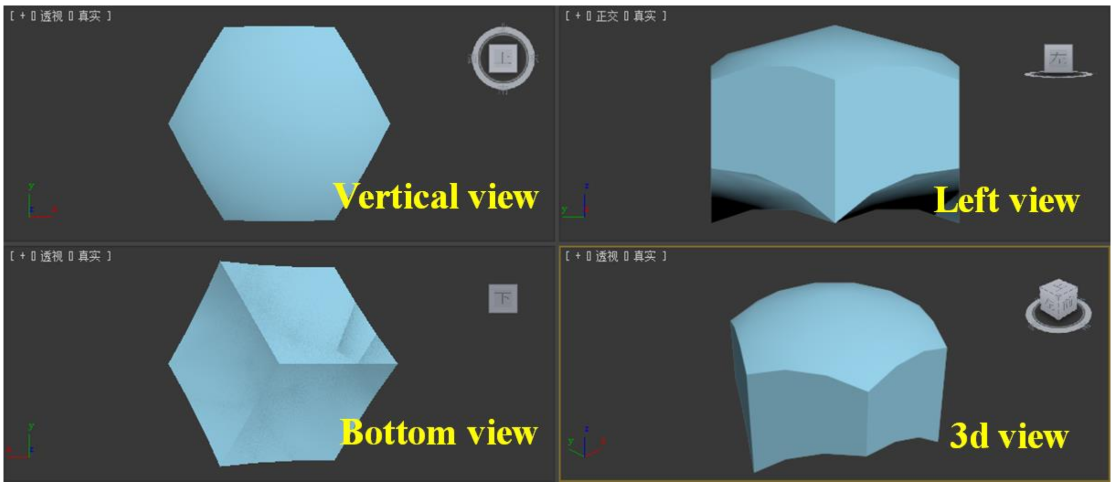

Fig.6 Three view drawing of foam cell model

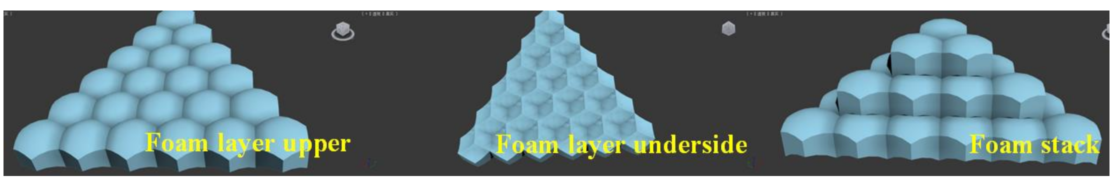

Fig.7 Model of foam layer and foam stack

The surface area of single bubble:

$$s = s_F + s_C \quad (1)$$

$$s_{平} \approx \left\{\left[h-\left(r-\sqrt{r^2-l^2}\right)\right]+h\right\}\times\frac{l}{2}\times 6 = 3l\left(2h-r+\sqrt{r^2-l^2}\right) \quad (2)$$

$$s_{曲} \approx 2\times 2\pi r\left(r-\sqrt{r^2-l^2}\right) = 4\pi r\left(r-\sqrt{r^2-l^2}\right) \quad (3)$$

s : the surface area of single bubble (m^2)

s_F : the flat surface area of single bubble (m^2)

s_C : the cured surface area of single bubble (m^2)

h: the side height of single bubble (m)

l: the hexagonal side length of single bubble in the bottom view (m)

r: radius of curvature of bubble sphere (m)

Three pieces which were cut from the bubble on the center axis, along the 120°angle of the top sphere were filled in the bottom of the bubble, forming hexagonal prisms which has equal-height with the single bubble. So the volume of the single bubble was equal to the equal-height hexagonal prisms as shown in Fig.8.

$$v = \frac{\sqrt{3}}{2} l^2 \times 6 \times h = 3\sqrt{3} h l^2 \tag{4}$$

v : the volume of single bubble (m^3)

Fig.8 Volume Schematic diagram

According to expansion rate of foam, the volume of foam solution per kg

$$V_1 \cdot p = V_2 \tag{5}$$

$$V_1 = V_2 \cdot \frac{s}{2v} \cdot d \tag{6}$$

$$d = \frac{2v}{sp} \tag{7}$$

P: expansion rate of foam

v_1 : the volume of foam solution per kg (m^3/kg)

v_2 : the volume of foam per kg (m^3/kg)

d: the thickness of the foam cell (m)

1.2 The heat transfer model between Hi-Ex foam and LNG liquid pool

To analyze the heat transfer between LNG and foam, the foam is split in two, foam cells and air in the foam cell. Because of the huge differential temperature about 206k and the boiling LNG, the foam start to collapsed and some water contents in the collapsed foam will be released and be cooled down forming ice. Some foam which is not collapsed will be frozen and form ice tube passages along the LNG vapor pathways.

So the teat transfer occurs between LNG and water in the foam, the equations of heat transfer and LNG mass evaporation as follows:

$$\mathrm{q_{cell}} = \kappa_{cell} \cdot \Delta T_{cell}$$

$$\Phi_{cell} = \kappa_{cell} \cdot A_{cell} \cdot \Delta T_{cell}$$

$$m_{\mathrm{cell}} = \frac{\Phi_{cell}}{L} = \mathrm{q}_{cell} \cdot \frac{A_{cell}}{L}$$

$$M_{\mathrm{cell}} = \int_0^t q_{cell} \cdot \frac{A_{cell}}{L} dt = \frac{A_{cell}}{L} \cdot \int_0^t q_{cell} \cdot dt (0 \le t \le t_1)$$

A_{cell} : the contact area of LNG pool surface and foam (m^2)

ΔT_{cell} : the temperature difference of LNG and foam(k)

κ_{cell} : the convective heat transfer coefficient of LNG and foam solution($W/(m^2 \cdot K)$

q_{cell} : the heat flux of LNG pool and foam(W/m^2)

Φ_{cell} : the heat flow from foam to LNG pool(W)

m_{cell} : the LNG evaporation rate on account of heat flow from foam to LNG pool(kg/s)

M_{cell} : the LNG evaporation mass on account of heat flow from foam to LNG pool(kg)

L:the latent heat of LNG vaporization(J/kg)

t:time after foam application(s)

t_1 : the time when ice layer is formed, which means the heat transfer process has reached the steady state (s)

The heat transfer occurs between LNG and the air in the foam cell, the equations of heat transfer and LNG mass evaporation as follows:

$$\mathrm{q_{air}} = \kappa_{air} \cdot \Delta T_{air}$$

$$\Phi_{\text{air}} = \kappa_{air} \cdot A_{air} \cdot \Delta T_{air}$$

$$m_{\text{air}} = \frac{\Phi_{air}}{L} = \text{q}_{air} \cdot \frac{A_{air}}{L}$$

$$M_{\text{air}} = \int_0^t q_{air} \cdot \frac{A_{air}}{L} dt = \frac{A_{air}}{L} \cdot \int_0^t q_{qir} \cdot dt (0 \le t \le t_1)$$

A_{air} : the contact area of LNG pool surface and air in the foam (m^2)

ΔT_{air} : the temperature difference of LNG and air in the foam(k)

κ_{air} : the convective heat transfer coefficient of LNG and air in the foam($W/(m^2 \cdot K)$)

q_{air} : the heat flux of LNG pool and air in the foam(W/m^2)

Φ_{air} : the heat flow from air in the foam to LNG pool(W)

m_{air} : the LNG evaporation rate on account of heat flow from air in the foam to LNG pool(kg/s)

M_{air} : the LNG evaporation mass on account of heat flow from air in the foam to LNG pool(kg)

3. The physical structure of ice layer and heat transfer model between LNG and ice

2.1 Characterizing the physical structure of ice layer

The structure of ice layer was complex as shown in Fig.4. The boundary layer was obvious with the side view. Above the boundary was the loose frozen foam and below it was the tight ice,which was the ice layer mentioned in the paper. The main body of ice layer was ice circle with uneven tentacles below it. Based on the above observation, the physical structure is developed as shown in Fig.9.

Fig.9 Model of the ice

2.2 Heat transfer model between LNG and ice layer

The bottom of ice layer contacted with LNG pool directly. The heat transfer between LNG and ice layer was divided into two pats. One part is the heat transfer between ice layer without tentacles between LNG, an assumption is given the water in foam does not flow downward, the transmission medium of heat transfer between foam, water and LNG is layer without tentacles, the equations of heat transfer and LNG mass evaporation as follows:

$$\mathrm{q}_{\mathrm{ice}} = \kappa_{ice} \cdot \Delta T_{ice}$$

$$\Phi_{\mathrm{ice}} = \kappa_{ice} \cdot A_{ice} \cdot \Delta T_{ice}$$

$$m_{\mathrm{ice}} = \frac{\Phi_{ice}}{L} = \mathrm{q}_{ice} \cdot \frac{A_{ice}}{L}$$

$$M_{\mathrm{ice}} = \int_{t_1}^{t} q_{ice} \cdot \frac{A_{ice}}{L} dt = \frac{A_{ice}}{L} \cdot \int_{t_1}^{t} q_{ice} \cdot dt (t \geq t_1)$$

A_{ice}: the contact area of LNG pool surface and ice layer (m^2)

ΔT_{ice}: the temperature difference of LNG and ice(k)

κ_{ice}: the convective heat transfer coefficient of LNG and ice($W/(m^2 \cdot K)$)

$\mathrm{q}_{\mathrm{ice}}$: the heat flux of LNG pool and air in the foam(W/m^2)

Φ_{ice}: the heat flow from ice to LNG pool(W)

$\mathrm{m}_{\mathrm{ice}}$: the LNG evaporation rate on account of heat flow from ice to LNG pool(kg/s)

M_{ice}: the LNG evaporation mass on account of heat flow from ice to LNG(kg)

The temperature field differential equation between LNG and tentacles as follows:

$$\frac{d^2 (\Delta T_{tentacle})}{dx^2} - \frac{\kappa_{tentacle} u_{tentacle}}{\lambda_{tentacle} \alpha_{tentacle}} \cdot (\Delta T_{tentacle}) = 0$$

$$\mathrm{u}_{tentacle} = 2 \cdot \pi \cdot r_{tentacle}$$

$$\alpha_{\mathrm{tentacle}} = \pi \cdot \mathrm{r}_{\mathrm{tentacle}}^2$$

x : the distance between the tentacle and bottom of ice(m)

$\mathrm{u}_{\mathrm{tentacle}}$: the cross sectional perimeter of single tentacle(m)

$\alpha_{\mathrm{tentacle}}$: the cross sectional area of single tentacle(m^2)

$\Delta T_{\mathrm{tentacle}}$: the temperature difference between LNG liquid pool(K)

κ_{tentacle} : the convective heat transfer coefficient of LNG and tentacles ($W/(m^2 \cdot K)$)

$\lambda_{\text{tentacle}}$: the heat conductivity coefficient of tentacles($W/(m \cdot k)$)

An assumption is given here that $\frac{\kappa_{\text{tentacle}} u_{tentacle}}{\lambda_{tentacle} \alpha_{tentacle}} = \beta^2$, and the above formula can be expressed as follow:

$$\frac{d^2(\Delta T_{tentacle})}{dx^2} - \beta^2 \cdot (\Delta T_{tentacle}) = 0$$

The boundary condition is shown as follows:

$$\begin{cases} \Delta T_{tentacle}\big|_{x=0} = \Delta T_{tentacle、0} = T_{\text{tentacle、0}} - T_b \\ \left.\frac{d(\Delta T_{tentacle})}{dx}\right|_{x=H} = 0 \end{cases}$$

Regardless of the heat dissipation at the steady state, the equations of heat flow between LNG and tentacles as follow:

$$\Phi_{tentacle} = -n\lambda_{tentacle}\alpha_{tentacle}\left.\frac{d(\Delta T)}{dx}\right|_{x=0} = n\Delta T_{tentacle、0}\sqrt{\kappa_{\text{tentacle}} u_{tentacle} \lambda_{tentacle} \alpha_{tentacle}}\, th(\beta H)$$

$$\text{q}_{\text{tentacle}} = \frac{\Phi_{tentacle}}{\alpha_{tentacle}} = \text{n}\Delta T_{tentacle}\sqrt{\frac{\kappa_{tentacle} u_{tentacle} \lambda_{tentacle}}{\alpha_{tentacle}}} \cdot th(\beta H)$$

$$\text{m}_{tentacle} = \frac{\Phi_{tentacle}}{L} = q_{\text{tentacle}} \cdot \frac{A_{tentacle}}{L}$$

$$M_{\text{tentacle}} = \int_{t_1}^{t} q_{tentacle} \cdot \frac{A_{tentacle}}{L} dt = \frac{A_{tentacle}}{L} \cdot \int_{t_1}^{t} q_{tentacle} dt \quad (\text{t} \geq t_1)$$

Φ_{tentacle} : the heat flow from tentacles to LNG（W）

$\text{q}_{\text{tentacle}}$： the heat flux from tentacles to LNG(W/m^2)

$\text{m}_{tentacle}$: the LNG evaporation rate on account of heat flow from tentacles to LNG pool(kg/s)

M_{ice} : the LNG evaporation mass on account of heat flow from tentacles to LNG(kg)

4.Heat transfer model between LNG and ambient

Most of LNG spill pools were on the concrete grounds inside the fire dike, so LNG touched directly with the ground, dike, air as well as solar radiation. After foam application, the ice layer, frozen foam layer and unfrozen foam layer above the pool block the heat transfer effects of the surrounding air and solar radiation which can be ignored, so the heat flux and evaporation rate was just between LNG and concrete:

$$q = \frac{\lambda_{\text{concrete}} \cdot (\Delta T_{concrete})}{\sqrt{\alpha_{concrete} \cdot \pi \cdot t}}$$

$$\Phi_{\text{ground}} = q_{concrete} \cdot A = \frac{A}{\sqrt{\pi \cdot t}} \cdot \frac{\lambda_{concrete} \cdot (\Delta T_{concrete})}{\sqrt{\alpha_{concrete}}}$$

$$m_{concrete} = \frac{\Phi_{concrete}}{L} = q_{concrete} \cdot \frac{A}{L}$$

$$M_{concrete} = \int_0^t q_{concrete} \cdot \frac{A_{concrete}}{L} dt = \frac{A_{concrete}}{L} \cdot \int_0^t q_{concrete} dt$$

$\Delta T_{\text{concrete}}$: the temperature difference of LNG and concrete(k)

$\lambda_{\text{concrete}}$: the heat conductivity coefficient of concrete ground($W/(m \cdot k)$)

α_{concrete}: the thermal diffusion coefficient of concrete ground(m^2/s)

q_{concrete}: the heat flux of LNG pool and concrete ground(W/m^2)

Φ_{concrete}: the heat flow from concrete ground to LNG pool(W)

m_{concrete}: the LNG evaporation rate on account of heat flow from concrete ground to LNG pool(kg/s)

M_{ground}: the LNG evaporation mass on account of heat flow from concrete ground to LNG(kg)

5. The total heat transfer and evaporation model of LNG

The total heat transfer mathematical model of LNG liquid pool covered by Hi-Ex foam:

$$\Phi = \begin{cases} \kappa_{\text{cell}} \cdot A_{cell} \cdot \Delta T_{cell} + \kappa_{air} \cdot A_{air} \cdot \Delta T_{air} + \dfrac{A}{\sqrt{\pi \cdot t}} \cdot \dfrac{\lambda_{concrete} \cdot (\Delta T_{concrete})}{\sqrt{\alpha_{concrete}}} \ (0 \le t \le t_1) \\ \kappa_{ice} \cdot A_{ice} \cdot \Delta T_{ice} + n_{tentacle} \cdot \Delta T_{tentacle} \sqrt{\kappa_{tentacle} u_{tentacle} \lambda_{tentacle} a_{tentacle}} \cdot th(\beta H) + \dfrac{A}{\sqrt{\pi \cdot t}} \cdot \dfrac{\lambda_{concrete} \cdot (\Delta T_{concrete})}{\sqrt{\alpha_{concrete}}} \ (t \ge t_1) \end{cases}$$

The evaporation rate of LNG:

$$m = \frac{\Phi}{L}$$

Φ : the heat flux from the surrounding to LNG liquid pool (w)

m: the evaporation rate of LNG (kg/s)

L: the latent heat of evaporation of LNG

6. Conclusions

With observations of Hi-Ex foam and ice layer,the physical structures of Hi-Ex foam and ice layer were built; the method of calculating the thickness of single bubble was deduced; the heat transfer and evaporation mathematical model of LNG liquid pool covered by Hi-Ex foam was developed. But some physical property parameters in the model are difficult to determine, so empirical values should be adopted and some paramenters should be studied in the fruture work. In addition, the heat transfer betweend hypothermal LNG gas and foam, ice was not fully considered, and it needs further research. Furthermore the heat transfer and evaporation mathematical model of LNG liquid pool covered by Hi-Ex foam should be verified by experimental dates , so that it can have a guiding significance for safety analysis of LNG leakage accident.

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