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The dynamical thermal stress and temperature of the main member of LNG Carrier during pre-cooling process

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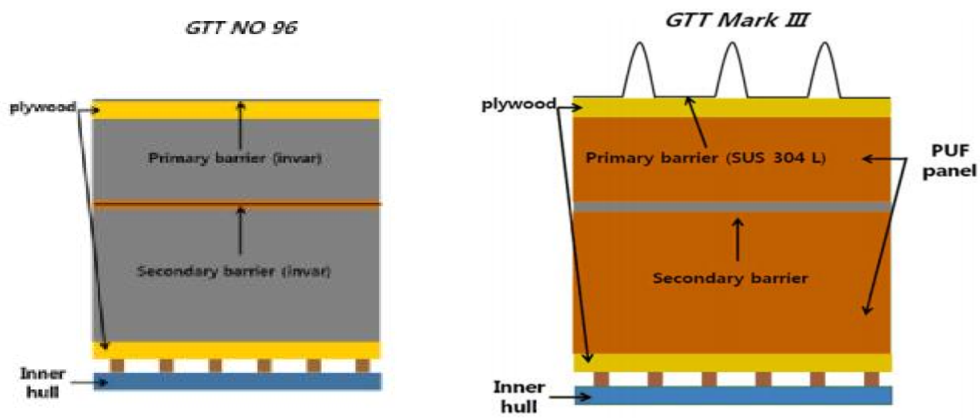
Abstract:the mathematical model of thermal stress field and temperature field are built for the main member lay with different dropping velocity of temperature.the analytic solutions for the temperature and thermal stress are obtained by the integration transformation.the numerical results are shown in Figs.The effects of the cooling velocity on the temperature and thermal stress are investigated.The faster the cooling velocity ,the greater temperature grades,and the bigger tensile thermal stress within the surface of the main member lay.this bring the dangerous influence on the brittle property of material in low temperature.

Introduction

Natural gas is of high efficiency, high quality and cleanness. It is becoming more and more popular. The natural gas reserves are rich, but uneven in the global distribution, mainly in the Middle East, Russia, North Africa and other regions. The density of natural gas is small, and its gas density is 1/625 of its liquid density. Natural gas is usually carried in liquid form through pipes and ship carrying vehicles. LNG ship is a high-tech ship, which is difficult to build and operate. LNG ships operating must be accordance with the operating procedures and specifications. Pre cooling process of cargo tank is one of the most important steps. Pre cooling is the cooling of ships and their pipelines prior to the ship loading of liquid natural gas. But the dropping rate of temperature is strictly controlled. The precooling operation effectively avoids excessive thermal stress in the retaining system and cabin structure,resulting from rapidly cooling.If cracks occurs on the surface of film (Invar steel material)of cargo tank. LNG leakage accidents may be take places, [1,2].

At present, the mainstream cargo tanks are MOSS type , NO.96 type and MarkIII type . Among them, NO.96 (Figure 1. (a)) and MarkIII (Figure 1 (b)) all belong to the film type liquid cargo tank. During pre cooling, liquid natural gas is pumped through the pipeline into the spray system at the top of the tank which is sprayed into the cargo compartment through the nozzle.the dropping rates of the temperature at the surface of the film are adjusted by controlling the injection volume Usually,The pre cooling time is more than 10 hours. The pre cooling time is entirely due to the cooling of the cargo cabin containment system. The longer it is, the safer it is, but the worse the economy is.

From the existing literature, the research on the thermal strength of the liquid tank focus on temperature field and thermal stress prediction [3,4], the impact strength of liquid cargo sloshing [5,6].So far, papers on pre cooling resulting in film cracking are very few. In this paper, the effect of different cooling rates on the thermal stress is investigated from the cracking mechanism point of view.



(a) (b)

Fig1.Film type enclosure structure of two types

The pre cooling transient temperature models

The aim of strictly limiting pre cooling speed to prevent excessive tension and cracking. Corresponding to Fig.. 1, the film of the enclosure structure is simplified as the Fig.2 physical model.

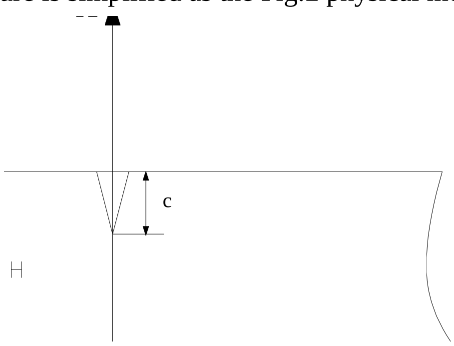


Fig.2 physical model of the film

The equation of heat conduction in the film is as following

$$\frac{\partial T}{\partial t}=a\frac{\partial^2 T}{\partial x^2} \qquad x>0,t>0 \tag{1}$$

In the precooling process, the flow rate of LNG is controlled by the valve to slow down the dropping velocity of the main membrane.the following functions are used to describe the temperature change of the main membrane wall (LNG)

$$\frac{T-T_0}{T_w-T_0}=1-\exp\left(-\frac{t}{t_0}\right) \qquad x=H,t>0 \tag{2}$$

where is T_0 initial temperature;T_w is the final temperature and $T_w<T_0$;t_0 denote time quantity of dropping velocity.

The insulating layer is attached to the another side,the boundary condition is as follow

$$\frac{\partial T}{\partial x}=0 \ \ x=0,t>0 \tag{3}$$

According to integral transformation method, the solution of Eq.(1) is written as in the case of Eq.(4).

$$q(h,x)=\sum_{m=1}^{\infty}2\cos(b_m h)\bar{q}(b_m,x) \tag{4}$$

where $\bar{q}(b_m,x)=\int_0^1 q(h,x)\cos(b_m h)dh$, $b_m=(m-0.5)p\ (m=1,2,\cdots)$.

$$q=\frac{T-T_0}{T_w-T_0}\ ,\quad h=\frac{x}{H}\ ,\quad x=\frac{at}{H^2}\ ,\quad b=\frac{at_0}{H^2} \tag{5}$$

Applying integrated transformation to Eq.(1),the analytic solution of the temperature is written as

$$q(h,x)=\frac{T-T_0}{T_w-T_0}=\sum_{m=1}^{\infty}2\left\{\frac{1}{b^2{}_m}-\frac{x_0}{x_0 b^2{}_m-1}\exp\left(-\frac{x}{x_0}\right)+\frac{1}{b^2{}_m(x_0 b^2{}_m-1)}\exp\left(-b^2{}_m x\right)\right\}\cos(b_m h) \tag{6}$$

The pre cooling thermal stress models

The interior points of the main membrane wall are only restrained in the transverse direction, and there is no shear strain in the other directions. The surface is free and unconstrained,therefore $s_{xz}=0$ and $s_{xy}=0$ .The considering compatibility equation , $\frac{d^2e_{yy}}{dx^2}=0$ is obtained, then solution of the displacement is written as $e_{yy}=Ax+B$,The stress-strain relation with temperature displacement is expressed as

$$s_{yy}(x,t)=E[Ax+B-a(T-T_0)] \tag{7}$$

The resultant force and resultant moments are zero at any cross section ,we have

$$\int_0^H s_{yy}dx=0 \qquad 和 \qquad \int_0^H xs_{yy}dx=0 \tag{8}$$

the dimensionless thermal stress is written as

$$s=6\left(2\int_0^1 hqdh-\int_0^1 qdh\right)h+2\left(2\int_0^1 qdh-3\int_0^1 hqdh\right)-q \tag{9}$$

where $s=\frac{s_{yy}}{Ea(T_w-T_0)}$

Numerical calculation and discussion

For the two types cargo tank, the Invar steel main membrane layer,resistant to low temperature materials,is taken as supported structure and its width is 0.07mm.The mechanical parameters of Invar steel are listed in table 1

Table 1.mechanical parameters of the Invar steel

name	width（mm）	heat conductivity（W/m.K）	thermal expansion coefficient（1/C）	modulus of Elasticity（GPa）	density（kg/m^3）	specific heat capacity（J/kg.C）
Inwar steel	0.7	60.4	1.5×10^{-6}	210	8130	480

The parameters related to precooling cargo tank is given as $T_0 = 20^{\circ}C, T_w = -120^{\circ}C$. The temperature variation of the different dropping velocity for the surface of the main membrane is plotted in Fig.3.The distribution of the temperature and thermal stress are shown in Fig.4~Fig.5.

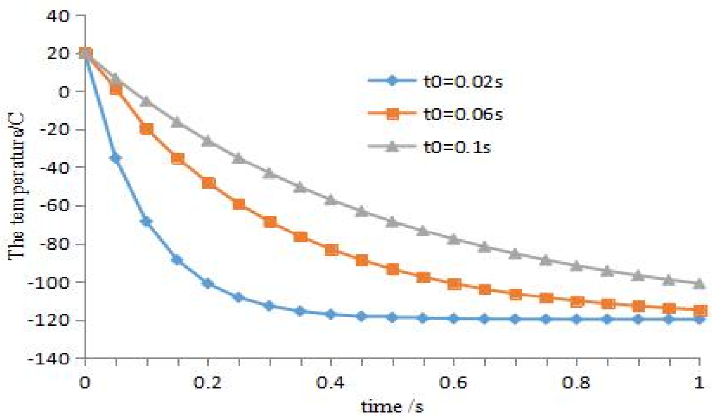


Fig.3.The variation of the surface

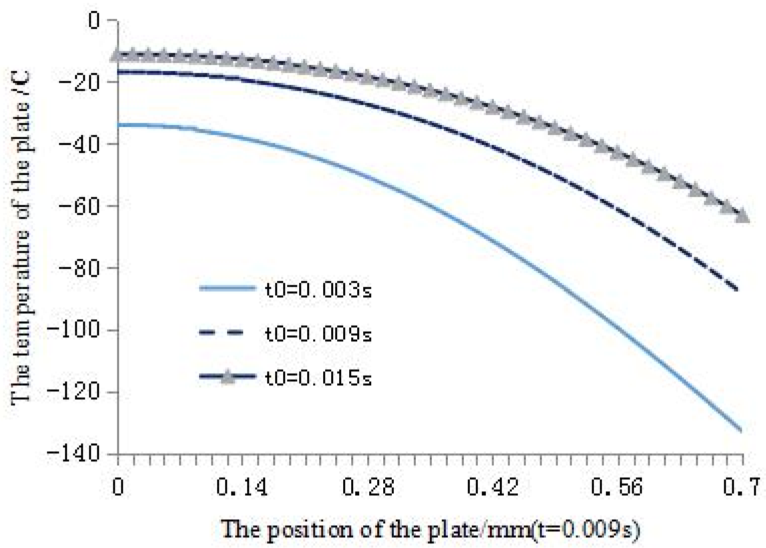


Fig.4The distribution of the temperature through main membrane

Fig. 4,5 shows temperature and thermal stress distribution corresponding to different cooling speed , it can be seen that the smaller the corresponding cooling rate is , large is temperature gradient in the main membrane wall and the larger the tensile stress is near the surface, the greater the compression stress at the middle area of main membrane, This properties may induce cracks of Invar steel, furthermore, if there are cracks in the welding process, the surface crack suddenly increased, resulting in LNG leakage, which is absolutely allowed in operation.

Conclusion

Based on pre cooling process properties of the main membrane wall .temperature field and thermal stress field mathematical model are established and the effect of cooling rate on the temperature and thermal stress. The numerical results show that the larger the cooling rate is, the greater the temperature gradient of the main membrane ,the greater the tensile stress near the surface, which has a very negative impact on the brittle behavior of the low-temperature metal.

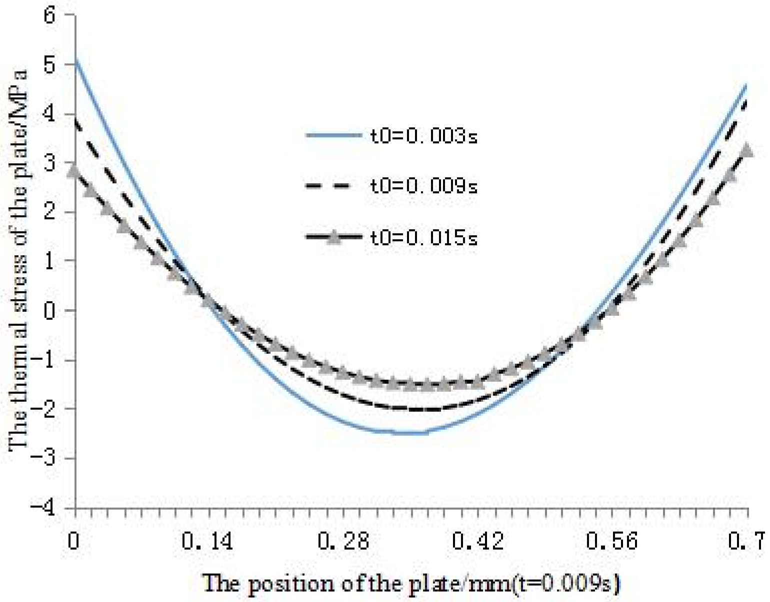


Fig.5The distribution of the thermal stress through main membrane

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