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Analysis of a new self-pressurization model for cryogenic fluid tank

Guopeng Wang^{1,2}, Jianguo Li¹, Yanan Zhao¹ and Guotong Hong^{1,2}

¹ Key Laboratory of Space Energy Conversion Technologies, Technical Institute of Physics and Chemistry CAS, Beijing, 100190 China

² University of Chinese Academy of Sciences, Beijing, 100190 China

E-mail: lijanguo@mail.ipc.ac.cn

Abstract. In order to analyse the self-pressurization of the cryogenic fluid tank more accurately and further understand the law of the cryogenic fluid storage, a new self-pressurization model considering the temperature gradient of the vapour is presented. This model uses one-dimension method to deal with the vapour phase and lumped parameter method to deal with the liquid phase. Another two classical self-pressurization models are used to compare with this model. Based on this model, the comparison between the computation and the experimental results is conducted. The calculated results show that when the tank is in low fill level, the computation is in agreement with the experiment, but in high fill level the difference increases. Experimental results indicate that the new model can properly predict the pressurization curves of the tank.

1. Introduction

The storage of the cryogenic fluid is becoming more and more important for many applications on the ground or in space such as the liquid natural gas (LNG) storage, liquid helium dewars used in the space telescopes and the zero boil off tanks. The self-pressurization of such tank is unavoidable because of the big temperature difference between the external environment and the storage temperature. This phenomenon will destroy the tank and cause danger for the whole system if the pressure is too high. Thus, it is necessary to predict the pressurization of the tank reasonably. There have been many models developed to predict the pressurization curves. Aydelott [1] proposed a homogeneous model which considered the vapor and liquid in the same temperature and all the energy absorbed were being used to increase the internal energy of the system. Gursu et al [2] developed a model which considered the temperature gradient in liquid and they compared their computation with the experimental results from spherical liquid hydrogen tank. The results showed that this model is more accurate than homogeneous model. Lin and Hasan [3] developed a simple conduction model in the liquid and coupled it to the pressurization model of Brown [4]. Barsi and Kassemi [5] developed a two-phase model which considered the momentum equation of the liquid and took the vapor as ideal gas. The results of this model are in agreement with low fill levels but discrepancy happens in other fill levels with non-uniform heating.

This paper develops a new thermal diffusion model which uses one-dimension method to deal with the vapor phase and lumped parameter method to deal with the liquid phase and the computation results are compared with the results of two kind of classical self-pressurization models as well as the



experimental results. Moreover, the effect of fill level and heating power to the self-pressurization curves is discussed.

2. Model descriptions

2.1. Homogeneous model and three region model.

The homogeneous model considers the vapor and liquid in the same temperature and all the energy absorbed is being used to increase the internal energy of the system. The pressure of the tank equals to the saturated vapor pressure. The volume of the tank is not changed. According to the first law of the thermodynamics

$$d(m_v u_v)/dt + d(m_l u_l)/dt = \dot{Q} \quad (1)$$

where m_v and m_l are the mass of the vapour and liquid respectively. \dot{Q} is the heat coming from the environment, u_v and u_l represent the specific internal energy of the vapour and liquid respectively which is the function of the temperature as showed by equation (2) where C_v and C_l represent the specific heat capacity of the vapour and liquid respectively.

$$u_v = C_v T \quad u_l = C_l T \quad (2)$$

The density of the system is constant. If the volume fraction of the liquid phase is φ and the volume the system is V , then the density of the fluid, ρ_s , can be expressed as equation (3) where ρ_v and ρ_l represent the density of the vapour and liquid respectively.

$$\rho_s = (m_v + m_l)V^{-1} = \rho_l \varphi + \rho_v (1 - \varphi) \quad (3)$$

then the equation (1) can be changed as (4)

$$d \left[\rho_l (\rho_s - \rho_v) (\rho_l - \rho_v)^{-1} C_l T + \rho_v (\rho_l - \rho_s) (\rho_l - \rho_v)^{-1} C_v T \right] / dt = \dot{Q} V^{-1} \quad (4)$$

In the saturation state ρ_l , ρ_v , C_l , C_v and T are the single-valued function of the pressure and the curve of the self-pressurization can be calculated. The three region model takes the fluid of the tank to three parts, the vapour, the liquid and the interface of the liquid and vapour. The lumped parameter method is used to deal with the liquid and vapour phase. The internal energy of the interface is ignored and the phase change is assumed to happen on the interface. The vapour is taken as ideal gas and the volume of the tank is not changed. According to the continuity and energy equation of the vapour, we can get that

$$(\rho_v V_v) / \partial t = -\dot{m} \quad (5)$$

$$\partial(\rho_v V_v h_v) / \partial t = \dot{Q}_1 - \dot{Q}_{f1} - \dot{m} h_{sv} \quad (6)$$

Where \dot{m} is the condensation of the vapour at the interface in unit time. \dot{Q}_1 is the heat leak of the vapour and \dot{Q}_{f1} is the heat from vapour to the interface. h_{sv} is the specific enthalpy of the saturated vapour. Also, according to the continuity and energy equation of the liquid,

$$\partial(\rho_l V_l) / \partial t = \dot{m} \quad (7)$$

$$\partial(\rho_l V_l h_l) / \partial t = \dot{Q}_2 - \dot{Q}_{f2} - \dot{m} h_{sl} \quad (8)$$

Where \dot{Q}_2 is the heat leak of the liquid and \dot{Q}_{f2} is the heat from the interface to the liquid and h_{sl} is the specific enthalpy of the saturated liquid. And with the state equation of the fluid, the curve of the self-pressurization can be calculated.

2.2. The new self-pressurization model

The phase change and the temperature gradient of the fluid have big influence on the self-pressurization of the cryogenic tank. In order to describe the phenomenon more accurately, a new model that contains factors above is developed. There are some assumptions in this model. First, the whole region in the tank is stagnant. Experiments show that the initial state of self-pressurization is not stationary but it doesn't last long. Second, the phase change in the tank only happens at the interface of liquid and vapour. The temperature of the interface is the saturation temperature. The hydrostatic pressure of the fluid is ignored too. Finally, the vapour region is governed by one-dimension thermal diffusion equation and the liquid region is dealt with lumped parameter method. The schematic diagram of the model is shown in Figure 1.

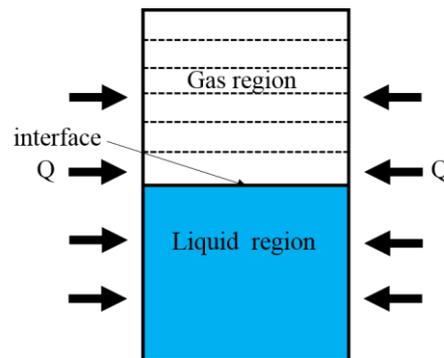


Figure 1. Schematic diagram of the model

The governing equation of the vapour is shown as (9)

$$\partial T / \partial t = a_v \partial^2 T / \partial z^2 + \dot{Q}_1 (\rho_v C_v)^{-1} \quad (9)$$

Where the a_v is the thermal diffusion coefficient of the vapour. Here z is the distance from the liquid/gas interface and \dot{Q}_1 is equivalent to a uniform internal heat source in this equation. The governing equation of lumped parameter method for liquid region is shown as (10)

$$\partial (\rho_l V_l h_l) / \partial t = \dot{Q}_2 + \dot{Q}_{in2} + \dot{m} h_{sl} \quad (10)$$

Where \dot{Q}_2 is the heat leak from the wall of the liquid region into the tank and the \dot{Q}_{in2} is the heat flux from interface to the inner liquid, \dot{m} is the mass flow of the interface and h_{sl} is the specific enthalpy of the liquid in saturation temperature. The simplified boundary condition on the interface is shown as (11)

$$\dot{m} = (\dot{Q}_{in1} - \dot{Q}_{in2}) \gamma^{-1} \quad (11)$$

Where γ is the specific latent heat of vaporization and \dot{Q}_{in1} is the heat flux on the vapor side of the interface. According to the model assumptions, the formula of \dot{Q}_{in1} and \dot{Q}_{in2} are shown as (12) and (13) where A is the area of the liquid/gas interface, λ_v and λ_l represent the thermal conductivity of the vapour and liquid respectively.

$$\dot{Q}_{in1} = - \left(\lambda_v A \frac{\partial T}{\partial z} \right) \quad (12)$$

$$\dot{Q}_{in2} = -A \frac{(T_{st} - T_l)}{2} \left[\frac{\lambda_l C_l (\rho_{st} + \rho_l)}{\Delta t} \right]^{1/2} \quad (13)$$

The boundary conditions and initial conditions are shown as (14)

$$z = 0, \partial T / \partial z = 0 \quad z = H, \partial T / \partial z = 0 \quad t = 0; T(z) = T_0 \quad (14)$$

According to the state equation of fluid, the pressure P and the other parameters can be obtained from the fluid property database of NIST.

3. The comparison of the computation and experiments

The comparison of the computation and the experimental results is shown in Figure 2, and the experimental results come from M Seo and S Jeong [6]. The geometric numbers of the cylindrical tank are 201 mm in diameter, 213 mm in height and 6.75 litres in internal volume. Four cases of the liquid volume fraction (0.1, 0.3, 0.5, 0.7) are considered.

Firstly, in the computation of three models, tank pressure increases with time and the rate is close to linear. And when the fill level of liquid increases, the pressure increasing rate is reduced. we can see that the pressure increasing rate of homogeneous model is the fastest in four different cases and its discrepancy is big compared with another two models. When the fill levels are 0.1 and 0.3, the computation of the new model is close to the three region model, but the increasing rate exceeds the three region model in another two fill levels.

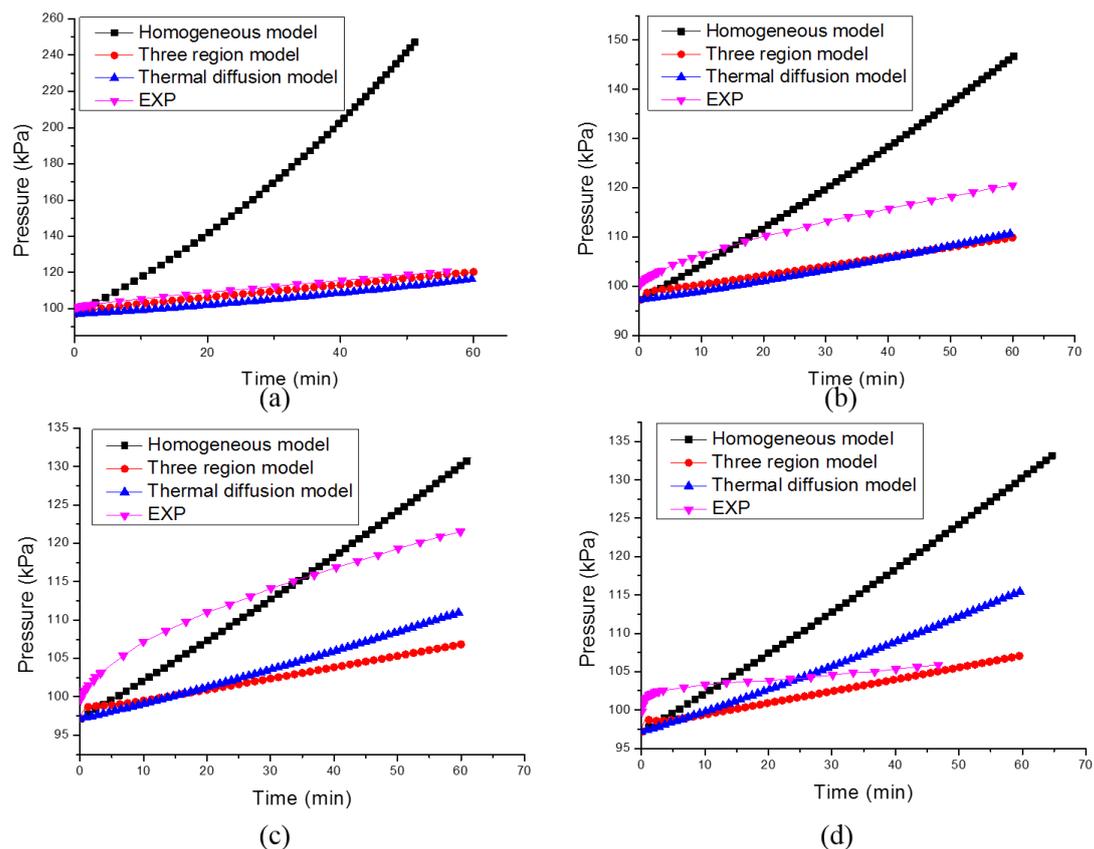


Figure 2. Comparison of the three kinds of model and the experimental results: (a) 0.1 liquid fraction, 0.8W heat leak, (b) 0.3 liquid fraction, 1.0W heat leak, (c) 0.5 liquid fraction, 1.2W heat leak, (d) 0.7 liquid fraction, 1.7W heat leak

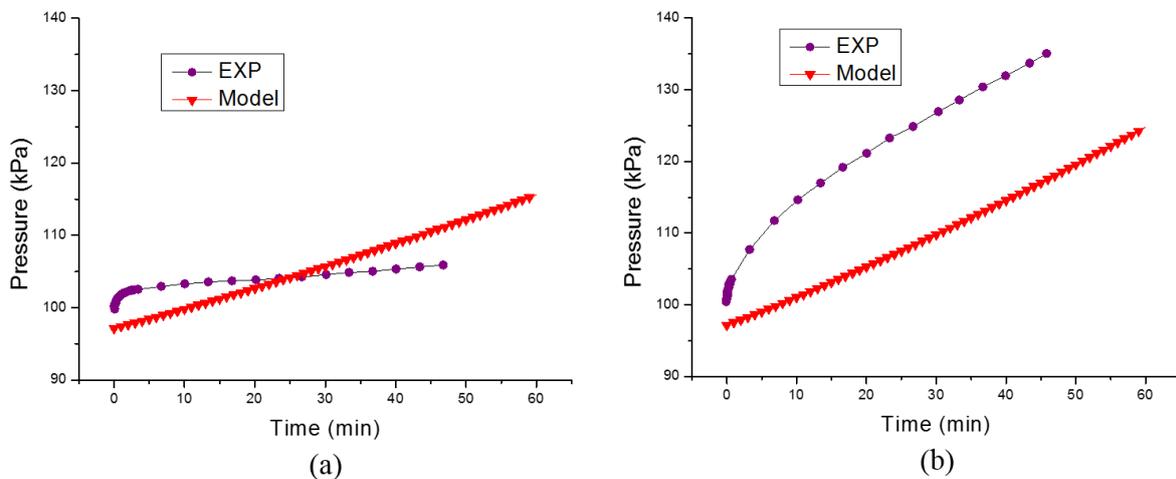


Figure 3. Comparison of the computation and experiment in fill level of 0.7: (a) 1.7W heat leak; (b) 2.5W heat leak

The fluid used in the experiment is LN₂ and the time of self-pressurization lasts 60 minutes. Results show that there exists a period that the pressure increases rapidly, but the time doesn't last long. In the computation of three models, this period doesn't exist. When the fill level of the tank is 0.1 and 0.3, the computation of three region model and the new (thermal diffusion) model have the same gradient as the experimental results. When the fill level is 0.5, the gradient of the new model is in better conformity with the experimental results, and when the fill level is about 0.7, the difference between the new model and the experimental result is becoming bigger with time going on. But when the heat leak increases from 1.7 W to 2.5 W and the fill level remain the same, the difference between the gradient of the experiment and computation is becoming smaller as shown in figure 3.

4. Discussion

The experiments show that at the beginning, the rate of increase of pressure is faster than equilibrium state, but the duration of this is short. During this time, the cryogenic liquid is still absorbing much heat from the LN₂ tank. During this initial phase, the generation rate of the vapour is faster than the equilibrium state, thus the rate of increase of pressure is high.

Figure 2 shows the comparison of the computation and the experiment results. As mentioned in section 3, the computation of homogeneous model has the biggest difference with the experimental data. When the fill level is lower than 0.5, the computation results of three region model and the new model show good agreement with the experimental results except the initial time. When the fill level is higher than 0.5, the discrepancy of the trend between three region model and the experimental data becomes bigger. At the fill level of 0.7, the difference of the slope between the new model and the experimental becomes big too. In the new model, lumped parameter method is used to deal with liquid phase while the natural convection and temperature stratification in this region is ignored, but vapour region is dealt with one-dimension method which means the temperature gradient in vapour is considered important. When the fill level of liquid is not very high, temperature gradient in vapour is obvious, and the volume of liquid is small which means the natural convection makes the liquid mix well, so temperature stratification in it is small. This case corresponds to the assumptions of the model. When the fill level is high, the temperature gradient in the vertical direction in the liquid becomes big and the temperature homogeneity in cross section becomes worse because of the natural convection near the wall. These factors can't be ignored anymore and the assumptions in model are not correspond to the actual cases, so the difference between computation and experiment becomes obvious. However, when the heat leak

of the tank increases from 1.7 W to 2.5 W in same fill level of 0.7, as shown in figure 3, the slope of two curves become consistent again, because the warm liquid near the wall moves up to the interface at the influence of buoyancy force and the fluid at interface moves to centre then moves down to the bottom. Such strong natural convection because of high heat leakage could make the liquid mix well, and thus the computation can be agreement with the experimental results again.

5. Conclusion

A new thermal diffusion model is built to predict the self-pressurization of the cryogenic tank which considers the phase change and the vapour temperature gradient. The comparison shows that the new model can reasonably predict the pressure change in a variety of fill levels. The discrepancy occurs between the new model and the data when there is low heat leak into the tank and high fill levels because there will be a significant temperature gradient in the liquid and natural convection in the liquid could not be ignored anymore.

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