2000

The Analysis of the Flow, Heat and Mass Transfer Process Inside a Cryogenic PH3 Trapper

X. Yuan
Xi'an Jiaotong University

X. Yang
Xi'an Jiaotong University

X. Li
Xi'an Jiaotong University

THE ANALYSIS OF THE FLOW, HEAT, AND MASS TRANSFER PROCESS INSIDE A CRYOGENIC PH_3 TRAPPER

Yuan Xiuling Yang Xiaoguang Li Xuexun
School of Energy and Power Engineering
Xi'an Jiaotong University,Xi'an,710049,P.R.China

ABSTRACT

In this paper, a mathematical model of condensation in a cryogenic PH_3 trapper with the presence of a non-condensable gas N_2 is developed, the calculation of the model is carried out and the mechanism of heat and mass transfer is theoretically studied. It also analyses the non-condensable gas N_2's effect on the condensing heat transfer of the PH_3 in the cryogenic trapper to obtain the following three changes by numerically computation: the temperature's change of the gas-liquid film interface with the change of the height of the cryogenic PH_3 trapper, the change of the liquid film's heat resistance and the total condensing resistance of the trapper, the change of the trapper's local heat transfer capacity, the change of the heat transfer coefficient of the trapper and the change of N_2's partial pressure.

INTRODUCTION

The flow in a cryogenic PH_3 trapper is a very complex physical process that includes thermosyphon and a phase change process that contains condensation, solidification and sublimation. Through the material we collected, it is found that there is hardly any research in the following fields: 1) two-phase change flow in concentric tube annulus with the presence of non-condensable gas; 2) convection heat transfer and mass transfer with multiple phase change processes; 3) the physical mechanism and mathematical model for sublimate of PH_3; 4) thermosyphon of PH_3-N_2 system. On the other hand, PH_3 is a kind of very important raw material for chemical industry, it is therefore meaningful to improve the technology of separating and purifying PH_3. At the same time, to understand the mechanism of flow with phase change is of the same importance for the design of heat exchanger, cooling of reactor and some other industrial processes. Consequently, it is indispensable to research into the physical process in PH_3-N_2 cryogenic trapper.

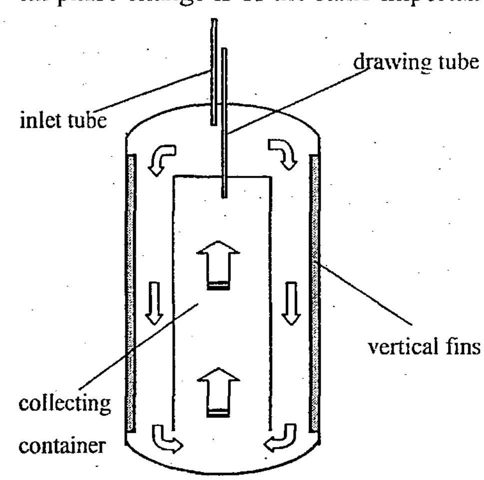

Figure 1 The schematic of the cryogenic PH_3 trapper

Because the heat transfer process is extremely complex, we will study the condensation, solidification, thermosyphon and sublimation separately. We also try to probe into the condensing heat transfer in the cryogenic trapper. The research into condensing heat transfer in cryogenic trapper is complicated by the existence of non-condensable gas N_2. But since 1980s, many scholars both domestic and abroad have researched into the condensing heat transfer of vapor/non-condensable gas system and made obvious progress. In 1980, Japanese researcher Hijikata Mori[1] gave out the unsimilar solution for body force condensing heat releasing. He divided body force condensing heat releasing in even concentration field into two different cases, one is that gas film and liquid film develop in the same direction and another is to develop in the opposite direction. He analyzed the phenomenon theoretically according to the molecular weight of the non-condensable gas. Wei Baotai[2,3] and some other researchers studied the condensation of Freon/Air system on a vertical plate. They set up relevant mathematical model on the basis of the condensation heat releasing model (the gas film and the liquid film develop in the opposite direction) which was given out by Hijikata. Hidefumi[4] studied the condensing heat transfer of the mixture of water vapor and N_2 in vertical tubes. There has been no public report of the research on condensing heat transfer of PH_3-N_2 system. Because PH_3 is severe toxic and volatile, it is essential to make some theoretical research.

ANALYTICAL MODEL

Referring to the mathematical model that was given out by Kunio-Hijikata[5] in 1973, the N_2 concentration in mainstream does not vary along the height of the condensing face, presenting a steady even concentration field.

The assumptions are:

- The shear stress at the liquid-vapor interface is assumed to be negligible;
- It is assumed that the variation of the fluid film's thickness along the X direction does not influence the two-phase boundary layer ;
- The boundary layer theory can be applied to liquid-gas two-phase boundary layer;
- The specific gravity of gas can be negligible in contrast to that of liquid;
- Pressure, properties are assumed to be constant, Reference Temperature is the temperature of the plate.

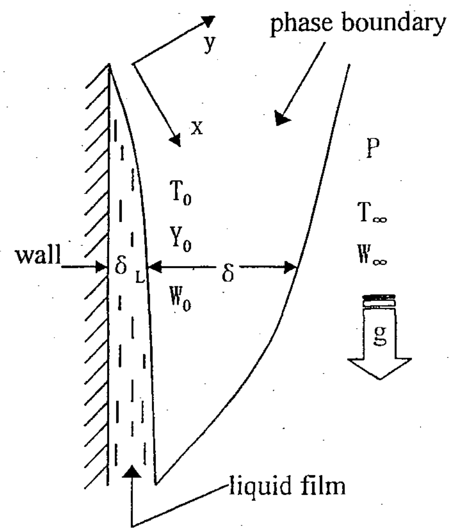

Figure 2 The schematic of condensation of liquid film

Fluid film:

Continuity:

$$\frac{\partial u_l}{\partial x}+\frac{\partial v_l}{\partial y}=0 \qquad (1)$$

Momentum:

$$\mu_l \frac{\partial^2 u_l}{\partial y^2}-\rho_l g=0 \qquad (2)$$

Energy:

$$\frac{\partial^2 T_l}{\partial y^2}=0 \qquad (3)$$

According to the assumptions, the theoretical solution given out by Nusselt is applied:

$$\dot{m} = \frac{g\gamma_l}{\nu_l}\delta_l^2 \frac{d\delta_l}{dx} \tag{4}$$

$$\dot{q} = \frac{\lambda_l \Delta\theta}{\delta_l} - \frac{3}{8}\frac{\gamma_l c_l \Delta\theta}{\nu_l}\delta_l^2 \frac{d\delta_l}{dx} \tag{5}$$

$$u_0 = \frac{g}{2\nu_l}\delta_l^2 \tag{6}$$

$\Delta\theta$ is the temperature drop in the liquid film.

Two-phase boundary layer:

Continuity:

$$\frac{\partial}{\partial x}\{(\rho + \rho_l)u\} + \frac{\partial}{\partial y}\{(\rho + \rho_l)v\} = 0 \tag{7}$$

ρ is the concentration of the mixture of PH_3 and N_2

$$\rho = \rho_g + \rho_v$$

$$\rho u = \rho_g u_g + \rho_v u_v, \quad \rho v = \rho_g v_g + \rho_v v_v$$

continuity equation of the non-condensable gas is

$$\frac{\partial}{\partial x}(\rho_g u_g) + \frac{\partial}{\partial y}(\rho_g v_g) = 0$$

Fick diffusion equation:

$$\rho_g(u - u_g) = \rho D \frac{\partial}{\partial x}\left(\frac{\rho_g}{\rho}\right) \tag{8}$$

$$\rho_g(v - v_g) = \rho D \frac{\partial}{\partial y}\left(\frac{\rho_g}{\rho}\right) \tag{9}$$

According to assumption 3), the diffusion along the X direction can be neglected, then we have:

$$u_g = u_v = u$$

Momentum: $$\frac{\partial}{\partial x}\{(\rho + \rho_l)u^2\} + \frac{\partial}{\partial y}\{(\rho + \rho_l)uv\} = (\rho + \rho_l - \rho_\infty)g + \frac{\partial}{\partial y}\mu\frac{\partial u}{\partial y} \tag{10}$$

Energy: $$\frac{\partial}{\partial x}\{(\rho_g h_g + \rho_v h_v + \rho_l h_l)u\} + \frac{\partial}{\partial y}\{(\rho_g h_g v_g + \rho_v h_v v_v + \rho_l h_l v)\} = \frac{\partial}{\partial y}\lambda\frac{\partial}{\partial y}T \tag{11}$$

h is the enthalpy which is defined as : (L is the latent heat of evaporation.)

$$h_g = C_{pg}(T - T_\infty), h_v = C_{pv}(T - T_\infty), h_l = C_l(T - T\infty) - L$$

To simplify the equation, two new variables are introduced:

$$w = \frac{\rho_v}{\rho} = \frac{\rho_v}{\rho_g + \rho_v}, \quad Y = \frac{\rho_l}{\rho} = \frac{\rho_l}{\rho_g + \rho_v}$$

The equation of two-phase boundary layer can be expressed as:

$$\frac{\partial}{\partial x}(1+Y)u^2 + \frac{\partial}{\partial y}(1+Y)uv = \left\{Y + \beta(T_\infty - T) + \frac{(M_g - M_v)(w_\infty - w)}{(1-w_\infty)M_v + w_\infty M_g}\right\}g + \nu\frac{\partial^2 u}{\partial y^2} \tag{12}$$

$$\begin{aligned}&\frac{\partial}{\partial x}\left[\{C_{pg} + w(C_{pv} - C_{pg}) + C_l Y\}(T_\infty - T) + LY\right]u + \\ &\frac{\partial}{\partial y}\left[\{C_{pg} + w(C_{pv} - C_{pg}) + C_l Y\}(T_\infty - T) + LY\right]v \\ &= -\frac{\lambda}{\rho}\frac{\partial^2 T}{\partial y^2} + D(C_{pv} - C_{pg})(T_\infty - T)\frac{\partial w}{\partial y}\end{aligned} \tag{13}$$

$$\frac{\partial}{\partial x}(1-w)u + \frac{\partial}{\partial y}(1-w)v = -D\frac{\partial^2 w}{\partial y^2} \tag{14}$$

$$\frac{\partial}{\partial x}(1+Y)u + \frac{\partial}{\partial y}(1+Y)v = 0 \tag{15}$$

$$w = F(T) \tag{16}$$

Boundary condition:

y=0: $\quad u = u_0, \quad v_g = 0 \quad \left(v = -\frac{D}{1-w_0}\left.\frac{\partial w}{\partial y}\right|_{y=0} \right)$

$\quad T = T_0, \quad w = w_0 = F(T_0)$

$y = \infty$: $\quad u = 0, T = T_\infty, w = w_\infty = F(T_\infty), Y = 0$

To meet with the boundary condition, the distribution of T, U, w and y in two-phase boundary layer is taken as following :

$$u = u_x\left(\varphi + \frac{y}{\delta_x}\right)\left(1 - \frac{y}{\delta_x}\right)^2, \quad Y = Y_0\left(1 - \frac{y}{\delta_x}\right)^2;$$

$$\frac{T_\infty - T}{\Delta T} = \left(1 - \frac{y}{\delta_x}\right)^n, \quad \frac{w_\infty - w}{\Delta w} = \left(1 - \frac{y}{\delta_x}\right)^2;$$

$$u_x \varphi = u_0, \quad \Delta T = T_\infty - T_0, \quad \Delta w = w_\infty - w_0$$

RESULT OF NUMERICAL COMPUTING AND ANALYSIS

Using the model established foregoing, we can numerically compute the condensation heat exchange in the trapper to get the influence law of non-condensable gas N_2 on heat exchange. Figure 3 expresses the variation of the liquid-gas film interface's temperature along the height of the trapper. It is obvious that because the fluid film's thickness increases along the height of the trapper, the fluid-gas interface's temperature increases gradually. This increasement with the N_2 concentration of 2.45% and 5% was calculated respectively in this paper. The interface's temperature increase with the N_2 concentration's increasement, hence the temperature difference for heat transfer decreases. This is the chief reason for the deterioration of heat exchange caused by non-condensable gas.

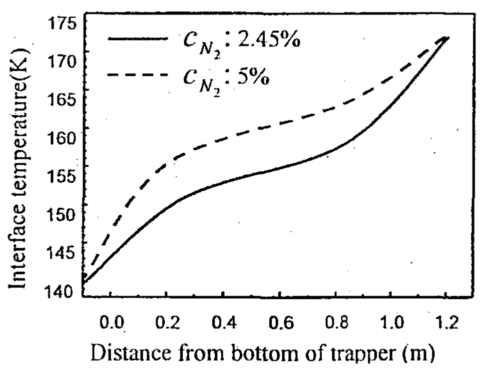

Figure 3 The interface temperature vs. distance from bottom of trapper

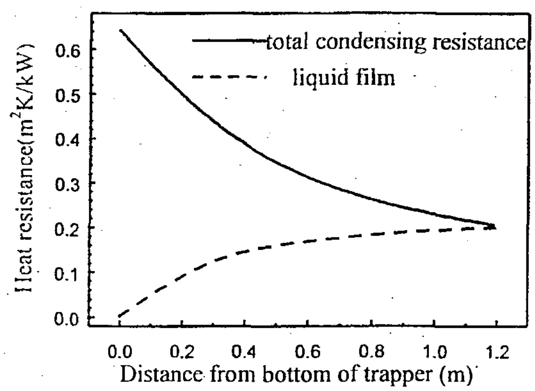

Figure 4 Heat resistance inside the trapper

Figure 4 expresses the variation of the thermal resistance of the whole heat transfer and of the liquid film along the height of the trapper. Because the fluid film's thickness increases along the height of the trapper, the thermal resistance increases in accordance. On the other hand, the whole thermal resistance of condensing heat transfer in the trapper decreases along the height of the trapper, the primary factor is that the thermal resistance caused by N_2 decreases sharply along the height of the trapper. Figure 4 does not express the variation of thermal resistance caused by N_2, but it is convenient to get to know that the difference between the total thermal resistance in the trapper with the fluid film's thermal resistance is the resistance caused by N_2. From the figure we know that the liquid film's thermal resistance is zero at the inlet of the trapper (where the height is zero). The total thermal resistance is actually the thermal resistance caused by N_2. Because the gas film develops in the opposite direction, its thickness at the bottom of the trapper (where the height is 1.2m) is

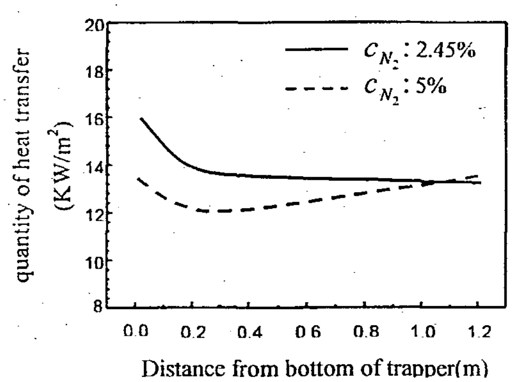

Figure 5 quantity of trapper's local heat transfer vs. distance from bottom of trapper zero. And the thermal resistance caused by N_2 is zero too, the total resistance in the trapper is the liquid film's thermal resistance .

Figure 5 expresses the change of the local heat flux in the trapper. Although it is known from figure 4 that the total thermal resistance decreases when the height of the trapper increases, the local heat flux does not change a lot along the height of the trapper, because the temperature difference for heat transfer has the same tendency as the total thermal resistance. The increasement of the local heat flux with the N_2 concentration of 2.45% and 5% was calculated respectively in this paper. High concentration of N_2 caused high thermal resistance and low local heat flux. We can learn this from figure 5. On the other hand, at the bottom of the trapper, the local heat flux increases while the concentration of N_2 increases. The reason is that the fluid film's thickness is small when the concentration of non-condensable gas is high. The intersection point of the two curves in figure 5 is actually the turning point between the controlling effect of liquid and gas film's thermal resistance. When x>p, the controlling factor is the liquid film. When x<p, the controlling factor is the gas film. In the condition of x >p, while the concentration of non-condensable gas is high, the thickness of liquid film is small, then its thermal resistance is small, and the temperature deference is great. This caused a high local heat flux. Hence a high concentration of non-condensable gas leads to a small total heat flow.

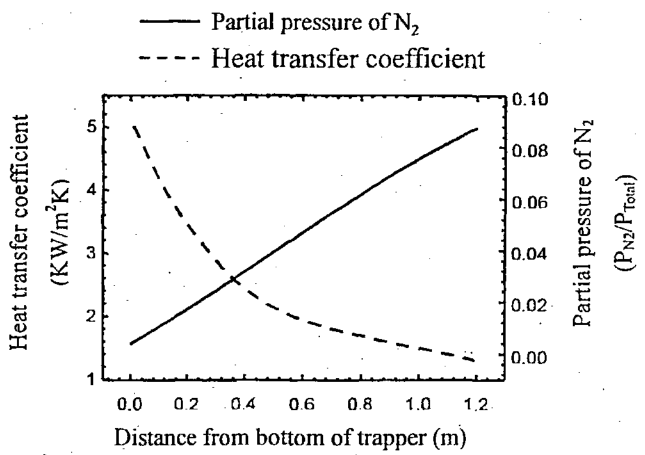

Figure 6 heat transfer coefficient and partial pressure of N_2 inside the trapper

Figure 6 expresses the heat transfer coefficient in the trapper and the partial pressure of N_2.

CONCLUSION

In this paper, a mathematical model of condensation in a cryogenic PH_3 trapper with the presence of a non-condensable gas N_2 is developed, the calculation of the model is carried out. The law of non-condensable gas N_2's effect on the condensing heat transfer of PH_3 is summarized. The following three changes are obtained by numerically computation: the temperature's change of the gas-fluid film interface with the change of the height of the cryogenic PH_3 trapper, the change of the liquid film's heat resistance and the total condensing resistance of the trapper, the change of the trapper's local heat transfer capacity, the change of the heat transfer coefficient of the trapper and the change of N_2's partial pressure. This paper provides scientific basis for the improvement of the construction of the cryogenic trapper and the intensification of heat transfer in the trapper.

ACKNOWLEDGEMENTS

The support of the National Natural Science Foundation of China through Grant No.29676034 is sincerely appreciated.

REFERENCES

1. K. Hijikata, Y. Mori and K.Utsunomiya, Nonsimilar solution of condensation heat transfer containing non-condensable gas, JSME.Trans.,46-408,B(1980)
2. Wei Baotai, An experimental study on laminar film condensation heat transfer of vapor with non-condensable gas on a vertical surface, Journal of Tianjin University,25(4), pp.9-14(1982)
3. Wei Baotai, Qiao Yueming and Liu Jing, Laminar film condensation of freon in the presence of air of nonhomogeneous concentration, Journal of Engineering Thermophysics, 8(3), pp.249-256(1987)
4. Hidefumi ARAKI, Yoshiyumi KATAOKA and Michio MURASE,Measurement of condensation heat transfer coefficient inside a vertical tube in the presence of non-condensable gas, J.of Nuclear Science and Tech.,32(6), pp.517-526(1995)
5. Y.Mori and K.Hijikata, Free convection condensation heat transfer with non-condensable gas on a vertical surface,Int.J.Heat Mass Transfer,Vol.16, pp.2229-2240(1973)