Review on Numerical Simulation of frosting behavior on Ambient air vaporizer

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ABSTRACT

Ambient air vaporizer is a heat exchanger, which utilizes environmental air to evaporate the fluid which is evaporating in the tubes of the device. Moist air from the ambient condenses on the tubes and freezes and forms frost. Long time operation leads to worsen the performance of the heat exchanger. Dynamic heat transfer due to frost formation and flow of cryogenic fluid is studied. Frost behavior on the vaporizer is also dependent on the flow rate of the fluid. Frost formation depends on the humidity, temperature of ambient air and mass flow rate, heat capacity and temperature of the cryogenic fluid. Ambient air based technology for gasifying cryogenic fluid is best for reducing the running cost of the terminals. Initially the outlet cryogen temperature surges due to the frost and then decreases with the passage of time. Frost formation is studied as one dimensional transient formulation with growing boundary and densification taking place as time elapses. Operation shows that with time the lengths of liquid-phase and two-phase sections increase, whereas that of the vapor-phase section decreases. Study of the dynamic heat and mass transfer is required for the optimal design of the ambient air vaporizer.

Keyword: - *Ambient air vaporizer, Frost formation, Heat and mass transfer, Cryogenic Heat transfer, Dynamic heat and mass transfer, LNG etc.*

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1. INTRODUCTION

Different cryogens can be liquefied down to 112 k under atmospheric conditions. This can also be done by using very high pressure in order to produce liquefied natural gas. Liquefaction of natural gas makes the transportation much easier because it greatly reduces the volume of natural gas by 600 times [1]. When LNG transportation is over, LNG vaporizers, e.g. ambient air vaporizers (AAV) are designed for the vaporization of LNG in gas terminal stations. AAV is widely used in small and medium gas terminal stations due to the low operation cost and high environmental sustainability. AAV has a group of parallel fin tubes, and the most common AAV fin tube is with 8 fins or 12 fins in a group. AAV utilizes ambient air to heat the cryogenic LNG inside the fin tube. Generally, LNG flows into the bottom of the fin tube, and natural gas flows out of the fin tube. The outlet temperature of natural gas should follow the requirement of the natural gas pipeline. The heat transfer performance of AAV is easily affected by the atmospheric conditions and operation parameters, e.g. temperature and humidity of the ambient air. The temperature difference between ambient air and LNG in the tube is the driving force of heat transfer. Therefore, the ambient air temperature can affect the heat transfer coefficient, especially in cold areas, where the outlet temperature of the natural gas usually cannot satisfy the requirement of the natural gas pipelines. This means that the climate conditions of different areas should be considered to design the AAV [2]. On the other hand, the cryogenic LNG may cause frost formation on the surface of the AAV fin tube. Frost layer makes the AAV ineffective because of the worse heat transfer coefficient, and thus a second AAV has to be employed to let the first AAV defrost. This is why the operation time for a certain type of AAV needs to be restricted. Otherwise, it will result in operating failures [3].

Jeong estimated the convective heat transfer of the AAV fins using computational fluid dynamics (CFD) with the assumption that the average outer surface temperature of the AAV fin tube was the same as the inlet temperature of LNG [4]. The optimal design of AAV fin geometries was numerically studied by analysing the thickness of frost deposit on AAV fins [5]. Gavelli presented a CFD-based modelling approach to predict the formation and dispersion of a fog cloud due to AAV operation. The effects of wind speed on the behaviour of the fog cloud around AAV unit was investigated [6]. During the process of LNG vaporization in the AAV, heat is transferred from the air to LNG due to the huge temperature difference. Cryogenic LNG flows into the AAV fin tube and flows out in the form of natural gas (NG) after absorbing enough heat from the air. Meanwhile, the fin tube and the ambient air are cooled down, leading to cryogenic frost formation as the operation time lasts.

The heat transfer process in AAV is very complex, some assumptions were made to simplify the model: the thermos physical parameters of the frost are uniform; the frost growth is one dimensional; the moist air on the cryogenic frost layer surface is saturated; the blockage effect of the frost layer on the air natural convection is negligible; the heat transfer by radiation is negligible.

1.1 Frost formation

Frost formation depends on the temperature and the partial pressure of the water vapour. There are two basic types of frost formation: (1) First type is that the vapour condenses into water drops firstly and then freezes into frost crystal (2) Second type is that the vapour freezes into frost crystal directly. The boundary of the frost formation type is the partial pressure of the water vapour. Although the temperature of the cryogenic surface of the AAV fin tube is much lower than the triple point of water, the frost crystal may not form if the partial pressure of water vapour was not in the proper range. Furthermore, the continuous accumulation of the frost crystal is essential to form the frost layer. The concentration gradient of the water vapour between the ambient air and the moist air around the AAV fin tubes is the driving force of the frost formation.

The mathematical model of the frost formation on the cryogenic surface is based on the conservation laws of mass and energy. The model is similar with the frost formation on the cold surface. However, the definite solution condition of the conservation equations is quite different. The empirical correlations of the density and thermal conductivity of frost layer on the cryogenic surface were adopted to solve the equations. According to the convective mass transfer, the water molecule passes from the air into the frost layer via the gas-solid interface. The mass growth of the frost layer equals to the convective mass transfer rate.

Degradation of performance is attributed to two reasons. First is frost having lower thermal conductivity, hence growth of frost on surface causes addition of thermal resistance which degrades the performance of heat exchanger. Second due to accumulation of frost; flow passages gets blocked and hence decreased flow rate of air ultimately results in reduction in heat duty.

Frost formation on evaporator surfaces under operating conditions of various freezers and refrigeration systems occurs inevitably, and frost formation results in a reduction in the heat transfer rate and the blockage of flow passage and hence decreases the design capacity of the equipment that is rated at the dry condition. Thus process in which heat is transferred to a refrigerated surface with the simultaneous deposit of a frost layer are important in gas coolers, refrigeration, regenerators, freeze-out purification of gases, cryo-pumping, gas re-gasification of cryogenic liquid and the storage of cryogenic liquids.

Another practical application of the frosting process is found in the aerospace industry. In this industry frost deposits are found to give both positive as well as negative effect. Frost accumulation on un-insulated missile fuel tanks partially insulate the Oxygen supply from external heat leak, thus reducing the amount of liquid required for 'topping' before firing. But the accumulated frost adds an undesirable weight to the missile and also creates unknown drag.

In the frost layer full growth period, the frost layer does not change its shape especially until the frost surface temperature comes to 0°C.The frost surface then begins to melt the melted water soaks into the frost layer and freezes into the ice form. This melting and freezing cause a sudden increase in the frost layer density and thus sudden decrease in its thermal resistance, which causes surface temperature decrement which again causes the frost deposition.

Kim studied the heat transfer behavior and frost formation numerically on the surface of un-insulated cryogenic tank filled with oxygen. Frost formation was modeled by considering water vapor diffusion into the frost layer. Heat transfer mechanisms considered was latent heat, natural convection, forced convection, radiation from ambient and solar radiation. Calculated results were first validated with available results from published literature which showed favorable agreement on thickness and frost thermal conductivity. Thereafter series of parametric studies was presented to understand the effect of parameters like wind speed of ambient air, air humidity, and tank wall temperature on the frost formation and heat transferred into tank. It was concluded that solar radiation also plays significant role in heat transfer, in some conditions heat transfer to the frost surface by latent heat can exceed the sensible heat transfer. It was observed that heat transfer strongly depends on ambient air temperature, air humidity and wind speed whereas doesn't depend much on tank wall temperature [7].

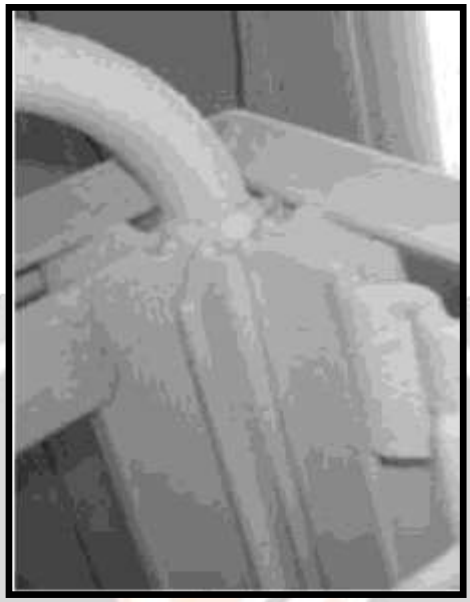

Fig -1 Frosting on finned tube heat exchanger

According to the convective mass transfer, the water molecule passes from the air into the frost layer via the gas-solid interface. The mass growth of the frost layer equals to the convective mass transfer rate.
C.J.L Hermes presented simplified analytical model which giving an explicit algebraic relation to predict the frost formation. The need for the simple analytical relation was felt due to the fact that despite the abundant literature in the field still explicit algebraic relationship was not available. Thus in this paper a dimensionless model based on macroscopic approach using energy and mass conservation within the frost layer was solved analytically to get an algebraic equation for the frost thickness with respect to time. Derived dimensionless expression was function of independent parameters like the super-saturation degree, air-to-surface temperature difference, and the Nusselt number that drive both the growth and densification of a frost layer. In their model temperature profile within the frost was assumed to be linear thus in-spite of modeling frost layer; a lumped approach was adopted to get frost surface temperature. The model results for the frost thickness were validated with published experimental data, and model predictions were found to agree well with experimental data. The formulation was also used to assess the influences of humidity, air to surface temperature difference, and Nusselt number on the frost thickness, it was found that humidity and Nusselt number were found to have major effect on frost layer formation while surface to air temperature difference was found to have minor effect. Being very simple to implement and providing clear effect of key parameters driving frost formation, the proposed formulation requires a very low computational effort. Thus it provides suitable tool for frost prediction in complex geometries which needs distributed simulation models having a large number of control volumes and thus more simulation time and complex coding for simulation [8].

Max Kandula prepared numerical model for predicting frost formation, their investigation was on flat surface under forced convection in laminar region. In their study previously developed non-dimensional frost density correlation was used which was function of Reynolds number and frost surface temperature. Similar to many other authors he also assumed frost surface temperature to be in saturated state and uniform density in their numerical model [9].

1.2 Flow boiling

Research into the phenomenon of heat transfer and pressure drop taking place in the vaporizer tubes carrying cryogenic fluids as well as different refrigerants has been carried out by numerous researchers. The researchers have used different correlations to evaluate the heat transfer and pressure drop taking place inside the vaporizer tubes. Among the widely used correlations, few are (1) Shah correlation (Intensification model) (2) Kandlikar correlation (Superposition model) (3) Chen correlation (Asymptotic model). The researchers have also worked on the identification of various flow regimes inside the vaporizer tubes. One other field of interest for many researchers over the last few decades regarding the in-tube vaporization process is the accumulation of frost on the surface of vaporizer tubes. Various researches have been conducted to predict the frost characteristics and frost growth process taking place in various heat exchanger configurations.
According to the results derived by the comparison of several correlations in the two phase flow and review of various literatures one distinguishes that: The two existing phenomena in the saturated regime "the nucleate boiling and the convective boiling" develop themselves in an inverse manner; the increase of one of the two generates the decrease of the other.

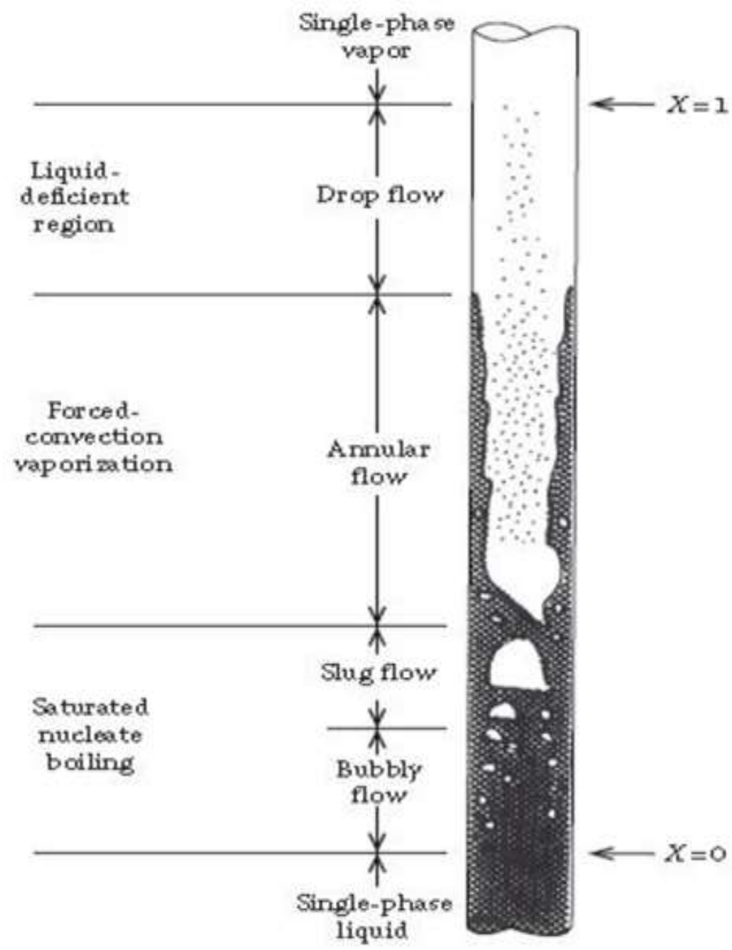

Fig -2 Flow patterns during forced convection boiling inside a tube

The Kandlikar correlation present the more logical results, because the coefficient of heat transfers re-assemble the two numbers (boiling number and convection number); as it gives the nature flow regime in the tube. For (Co < 0.65) high quality, and for (Co > 0.65) it is the low quality; as well as the coefficient of heat transfer increases with the increase of heat flux, itself that is just. The two coefficients (*hnb* and *hcb*) of the Kandlikar correlation includes

the same dimensionless groups and to choose one of the two truths value of transfer coefficient *h* don't suppress the parameters of basis used in the comprehension of the phenomenon mechanisms.
Whereas, the Chen correlation and the Shah correlation show that the heat flux is independent of heat transfer coefficient, although the studies and the experiences made since the antique show that the increase of heat flux provokes the increase of heat transfer coefficient. To choose *h* = max (*hnb* , *hcb*) in the correlation of Chen or Shah, made lose quite a lot of information and parameters used in the process of the beginning. We were also able to get an overview of enhanced heat transfer technology, along with citing recent developments. Also in the scope of the related paper, it was found that some of the active enhancement techniques that are used to enhance the flow boiling are not found to be promising. For instance, neither surface vibration nor fluid vibration have any effect on developed boiling or Critical heat flux (CHF). The same result was observed with the injection and electrostatic fields. This suggests that the active techniques should be reserved for the pool boiling, or possibly low velocity flow boiling, where the convective conditions still influence the boiling curve.

2. MATHEMATICAL MODELLING OF FROST AND FLOW BOILING

Introduction related your research work Introduction related your research work Introduction related your research work Introduction related your research work Introduction related your research work Introduction related your research work Introduction related your research work.
Main Governing equations of frost formation model.

1. Energy equation.
2. Mass conservation Equation (Densification), $\partial \varrho_{fr}/\partial t$.
3. Frost growth, $\partial H/\partial t$

2.1 Equations of the frost model

Heat transfer within frost is governed by One-dimensional energy equation as stated below,

$$\frac{\partial}{\partial x}\left(k_{fr}\frac{\partial T_{fr}}{\partial x}\right) + L_{sub}\frac{\partial \rho_{fr}}{\partial t} = \varrho_{fr} c_{p,fr}\frac{\partial T_{fr}}{\partial t}$$

Total vapor transferred from surrounding which is m_t can be found out by convective mass transfer.

$$m_t = h_m(\omega_a - \omega_{fs})$$

Mass diffused on frost surface m_d can be found out by fickian law of mass diffusion at frost surface. The above equations give the heat and mass transfer from the surrounding air and conduction inside the layers of the frost. The relation between the heat and mass transfer is given by the lewis analogy.

$$h_m = \frac{h}{\rho_a\, C_p\, Le^{\frac{2}{3}}}$$

3. CONCLUSIONS

(1) The thermal resistance of the cryogenic frost layer increases with the operation time, and its major influencing factor is the wall temperature of fin tube, followed by the air temperature and the relative humidity. There exists an ambient air temperature range named ‘peak thermal resistance temperature’ at about 255~261K depending on the operation time of the AAV. In this range the thermal resistance of the frost layer is much higher. In addition, the thermal resistance is higher when the relative humidity of the air is around 30% if other conditions are the same. Therefore, these two working conditions should be avoided for the operation of AAV in order to reduce the thermal resistance of the frost layer.
(2) The coupled dynamic heat transfer model incorporating the LNG flow boiling and the cryogenic frost formation works well and can provide theoretical basis for the better operation and design of the AAV.
(3) Frost formation on the AAV greatly affects the coupled heat transfer performance of the AAV, and the influence becomes stronger as the operation time goes on. The coupled heat transfer coefficient along the tube length is heavily influenced by the frost formation.
(4) According to the outlet temperature of natural gas, the effective operation time to switch the cycle of AAV can be obtained. For the same type of AAV, the effective operation time becomes shorter when the air temperature is lower.
(5) The simulated results indicate an initial surge in outlet temperature at the early stage, thus suggesting that the vaporizer can benefit from the frosting process. This surge decreases with ambient air temperature but increases with the flow rate of working fluid in the vaporizer. Besides, the surge lasts for a shorter time when the flow rate grows higher. Hence, it is more suitable for the AAV to work at low inlet mass flow rate for long time operation.
(6) When an AAV continues operating with a large inlet mass flux, the frost on the vaporizer fin thickens. Thermal resistance increases as a consequence. As a result, the lengths of the liquid-phase and the two-phase sections increase, and the vapour-phase section length decreases correspondingly. This directly causes the total heat exchange capacity of the vaporizer deteriorates, which is unexpected in engineering applications.

4. REFERENCES

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