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Review of vapor condensation heat and mass transfer in the presence of non-condensable gas

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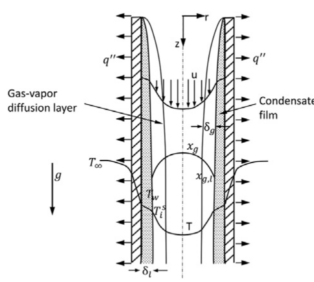
HIGHLIGHTS

- Filmwise condensation and dropwise condensation mechanism.
- Experimental works of several researchers are analyzed.
- Filmwise condensation in the present of NCG.
- Classify the physical models of heat transfer for filmwise condensation with NCG.

GRAPHICAL ABSTRACT



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ABSTRACT

In 1929, Donald Othmer discovered that a small amount of non-condensable gases (NCG) in pure vapor had a great effect on condensation heat transfer coefficient (HTC), reducing the efficiency of heat transfer equipment. Since then, a large amount of research has been performed. This paper reviews experimental, mechanism and model research progresses in condensation in the presence of NCG. Particular attention is given to research on physical models of heat transfer for filmwise condensation (FWC) with NCG, with a brief review of dropwise condensation (DWC). The models for FWC heat transfer in the presence of NCG can be divided into two categories: semi-theoretical models and theoretical models. The semi-theoretical models are based on hydraulics and thermodynamics, use some specific parameters of the correlation which determined by experiments, and are suitable for engineering design. The theoretical models are based on mass, momentum, and energy conservation equations, and divided into boundary layer models and diffusion layer models. Through research of experiments and models people found that, condensate film thickness, surface waves, interfacial shear strength and suction effect play an important role in the FWC heat transfer in presence of NCG.

1. Introduction

Condensation is defined as the removal of heat from a system in such a manner that vapor is converted into liquid. Vapor condensation includes filmwise condensation (FWC), atomization, and dropwise condensation (DWC), the last of which is difficult to obtain in industry [1]. Condensation heat transfer plays an important role in a variety of high-efficiency heat exchangers, such as heat pipes, nuclear industry reaction towers, and refrigeration and air conditioning radiators. However, it has a great effect on the condensation heat transfer coefficient when a small amount of NCG consists of pure vapor. In 1929, Donald Othmer [2] was the first to

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experimentally research the condensation of steam in the presence of NCG. In his experiment, he laid a copper tube horizontally with cooling water flowing through it up into a small boiler; the result showed that when the volume fraction of air in the boiler rose from 0 to 0.5%, the surface heat transfer coefficient of the copper tube fell by nearly 50%. After that, many researchers [3–6] experimentally studied condensation containing various kinds of gases, such as air, nitrogen, argon, neon, or hydrogen; vertical or horizontal surfaces; and forced or natural convection. The results of these studies showed that every kind of NCG would resist the condensation heat transfer.

In 1988, Wang and Tu [7] developed a simple physical model to research laminar FWC, consisting of a small amount of NCG in a vertical tube. They found that the effects of NCG on condensation were more significant in ducts than in unconfined surfaces, and that the lower the operating pressure, the more reduction in heat transfer. Then in the research [8] into forced convection FWC on a horizontal plate that was embedded in a porous medium, they similarly found about a 50% reduction in heat transfer efficiency induced by the presence of only 5% NCG.

These studies prove the NCG inhibitory effect on the processes of condensation heat transfer and mass transfer. This inhibition may reduce the heat exchange capacity of heat exchangers and also reduce the life of equipment. In some rare situations, such as the main evaporator of nuclear reactors, the accumulation of hydrogen and oxygen will cause an explosion [9,10]. Therefore, the influences of NCG on the thermal performance and accumulation performance are very important factors to be considered in the design of heat exchangers [11].

Unfortunately, in the steam condensation heat transfer system, there are many causes that induce the generation of NCG. The main reasons are if the heat pipe contains vacuum residuals, gasses or impurities dissolved in the working fluid, or a chemical reaction between the working fluid and case material [11,12]. Therefore, the presence of NCG in heat pipes is very common, especially in large industrial heat pipes.

Research into inhibiting the effects of NCG showed that an electric field [13] and a wave interface [14] can enhance the heat transfer coefficient. In a statistical experimental study, Kim et al. [15–17] showed that a wavy water film increased the heat transfer efficiency whether the NCG-containing vapor was on a horizontal or a vertical wall. They found that the air mass fraction, the mixture vapor velocity, and the condensate film Reynolds number of the surface waves on condensation affected the heat transfer coefficient. The vapor-side heat transfer coefficient clearly increased with the increase of the film Reynolds number. The enhancement effect was dominant for low mixture vapor velocity, but decreased with the increase of mixture vapor velocity. That is, whether on a horizontal wall or the vertical wall, the wave of the film condensation surface has a positive effect on condensation heat transfer. Sabir et al. [18] came to the same conclusion in their experiment, which studied the condensation heat transfer in the surface of lithium bromide/water in the presence of NCG in absorption refrigeration systems, such as air, nitrogen, argon and neon.

Rose [19] reviewed condensation on the outside of finned tubes, inside "microfinned" tubes, and in micro-channels, as well as dropwise condensation and pseudo-dropwise condensation, which can occur for binary mixtures. The review showed that surface tension played an important role in the enhancement of the condensation heat transfer, especially the Marangoni effect in the condensation process of micro channel and micro size, and that it could effectively promote the flow in the condensation surface and internal liquid film, as well as enhance heat transfer.

Of course, NCG can also be used to regulate gas in a variable conductance heat pipe (VCHP), so that the heat pipe can automatically keep its temperature constant even when external conditions are changed. VCHPs are usually used for thermal control in spacecraft and satellites [12].

The early studies of heat transfer for VCHPs were based mainly on a simple flat-front model. The model assumed that NCG formed a gas plug at the condenser end of the pipe, which acted as a diffusion barrier to the flowing vapor. The interface between the active and NCG-blocked portions of the pipe was very sharp, making it ideal for a vapor–gas mixture; the model also neglected axial conduction [12]. Subsequently, Edwards and Marcus [20] developed a 1D model for the prediction of heat transfer in VCHPs that showed a smooth decrease in the vapor concentration and a corresponding increase in NCG concentration along the axial of the pipe. Natural convection and tube wall axial conduction can influence this vapor-NCG front, and so the theory came closer to the actual situation; this model was called the diffusion front model, as shown on Fig. 1. Then Rohani and Tien [21] developed a steady 2D heat and mass transfer numerical analysis of VCHPs that use NCG, including the temperature distribution of vapor in the radial direction and therefore increasing the accuracy of the model.

However, these studies didn't consider the vapor diffusion in the radial direction, instead assuming that the vapor-NCG diffusion region was uniform in the radial. Hijikata et al. [22] considered that, in addition to the axial mass diffusion, the radial diffusion caused NCG to accumulate at the vapor–liquid interface, retarding vapor condensation. They developed a 2D diffusion model that gave two important dimensionless factors: the gas load L_g^* and the radial diffusion parameter E ($E = \rho_s D h_{fg}/[h_c\,(T_s - T_b)R]$), in which ρ_s is the saturated vapor density, D is Fick's diffusion coefficient, h_{fg} is the latent heat of vapor, h_c is the heat transfer coefficient from wall to coolant, T_s is the saturation temperature, T_b is the bulk temperature of coolant, and R is the pipe radius. The parameter E is the ratio of the radial gas rate to the vapor condensation rate. For a small value of E, radial diffusion is pronounced; at a larger value of E, the problem behaved more like the 1D diffuse model. Fig. 2 shows the schematic of the condenser in a two-phase closed thermosiphon. In the figure, the interface of NCG and vapor is not a homogeneous region of 1D model, but a parabolic-shaped region.

Peterson and Tien [23,24] established three levels of complexity for the theoretical treatment of the vapor-NCG front analysis: flat front, simplified analytical formulation, and numerical calculations that take into account the diffuse mass transport in the vapor-NCG interface region. These levels were used for different applications according to their characteristics. After a few years, many scholars [25–27] optimized and made revisions to the model in order to guide the design of VCHPs.

In conclusion, many studies indicate that a small amount of NCG can have a great inhibitory effect on the condensation of steam. Condensation heat transfer is common in heat pipe heat

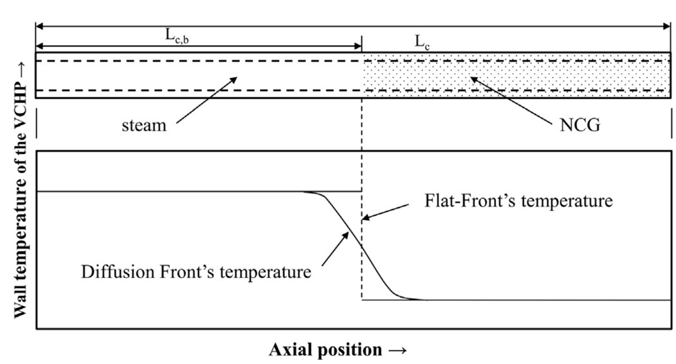

Fig. 1. Schematic of two models of VCHP [12].