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Flow and heat transfer characteristics of ambient air condensation on a horizontal cryogenic tube

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Ambient air condensation on a cryogenic horizontal tube is investigated using a newly built mathematical model, in which the liquid film and the vapor boundary layer are coupled together with a major emphasis on the effect of buoyancy. Based on the model, the heat transfer coefficients and the film thickness as well as the interfacial shear are obtained under different conditions to investigate the effects on the flow and heat transfer characteristics of the superheating between vapor and film, the buoyancy in the boundary layer and the subcooling between wall and film. In addition to the flow and heat transfer characteristics of air, the other four different vapors, *i.e.* H_2O, R134a, methane (CH_4), argon (Ar), are also discussed. The results show that the superheating has a more significant contribution to the increase of heat transfer coefficient for air comparing to the other vapors, *e.g.* in the cases of superheating $\Delta T_\infty = 100$ and 200 K the mean heat transfer coefficient increases by 10.3% and 24.3% for air, while it increases by only 1.8% and 3.9% for H_2O. In contrast to superheating, the subcooling has a negative effect on the increase of heat transfer coefficient. Noteworthy, the buoyancy plays a non-negligible role on the flow and heat transfer characteristics of superheated air condensation. The analytical results are of great importance in the design and improvement of ambient-heated cryogenic vaporizer (AHCV).

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1. Introduction

Liquid hydrogen (LH_2), featuring high specific impulse and non-toxicity, is a popular fuel in space missions. Usually, LH_2 is filled into the tank of rocket under the driving of high-pressure hydrogen, which is produced in an ambient-heated cryogenic vaporizer (AHCV) heated by the ambient air. Owing to the large temperature difference between LH_2 and ambient air in AHCV, the air (saturation temperature is 78.931 K [1]) could be condensed on the surface of the horizontal tubes. Therefore, understanding of the flow and heat transfer characteristics of air film condensation on the horizontal tubes is of great significance in the design of AHCV.

Film condensation is a common phenomenon in phase change heat transfer. Date to 1916, laminar filmwise condensation on flat vertical surfaces and horizontal cylinders placed in quiescent saturated vapors were analytically predicted by Nusselt [2]. In order to eliminate the limitations in Nusselt's model caused by the inherent assumptions, many researchers attempted to develop more accurate models. Shekriladze and Gomlauri [3] investigated the flowing vapor condensation considering the interfacial shear and realized that the phase conversion in momentum across the interface dominated the interfacial shear. Fujii et al. [4,5] proposed an approximate method to solve the two-phase boundary layer equations to investigate the laminar film condensation of flowing vapor on a vertical surface [4] and a horizontal cylinder [5], resulting in a good agreement with experiment results. Gaddis [6] strictly solved the two-phase boundary equations of liquid and vapor flowing perpendicular to a tube for laminar film condensation using series expansions. Rose [7] examined the influence of pressure gradient on the forced-convection film condensation on a horizontal tube. In the model, interfacial shear was approximated via a modification of Shekriladze and Gomlauri's [3] model, and the potential flow theory was utilized as well. Afterward, in order to design the engineering systems, *e.g.* power-plants, heat exchangers, refrigeration and aerospace [8], many effects on the film condensation have been addressed, including surface temperature [9–11], turbulent flow [12,13], wall suction [14–16], non-condensable gas [17–20] and others [21–25].

In the past, the majority of researchers in the field of film condensation focused on saturated vapor while few attentions were paid to superheated vapors. Minkowycz and Sparrow [26,27]

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Nomenclature

A_0,A_1,B_1,B_3	coefficients in Eqs. (46) and (47)
c_p	specific heat at constant pressure, J/(kg K)
d	diameter of tube, m
f	nondimensional number defined by Eq. (13)
g	gravitational acceleration, m/s^2
H_0,H	nondimensional number defined by Eqs. (22) and (25), respectively
h_{fg}	latent heat of condensation, J/kg
P	$\rho\mu$-ratio defined by Eq. (43)
Pr	Prandtl number of liquid film
r	radius of tube, m
T	temperature, K
ΔT_w	subcooling, $\Delta T_w = T_s - T_w$, K
ΔT_∞	superheating, $\Delta T_\infty = T_\infty - T_s$, K
u_R	reference velocity, m/s
u_L,u_V	tangential velocities of liquid and vapor, respectively, m/s
v_L,v_V	radial velocities of liquid and vapor, respectively, m/s
y	radial coordinate variable
z	nondimensional coordinate variable defined by Eq. (14)

Greek symbols

α	heat transfer coefficient, W/(m^2 K)
β	λ-ratio defined by Eq. (29)
γ	heat transfer increase coefficient defined by Eq. (53)
δ	thickness of the liquid film, m
Δ	thickness of the vapor boundary layer, m
λ	thermal conductivity, W/(m K)
λ_{Vs}	thermal conductivity of saturated vapor, W/(m K)
ξ	nondimensional coordinate variables define by Eq. (37)
μ	dynamic viscosity, (Pa s)
ν	kinematic viscosity, m^2/s
ρ	density, kg/m^3
σ	ratio of the liquid film thickness to the vapor boundary layer thickness, $\sigma = \delta/\Delta$
τ	interfacial shear, Pa
φ	angle measured by radian

Superscripts

*	nondimensional quantities

Subscripts

L	liquid
V	vapor
s,0	saturated state
w	tube wall
φ	local value at angle φ
Δ	value at the outer edge of vapor boundary layer
δ	value at the liquid–vapor interface
∞	value outside the vapor boundary layer

studied the condensation of superheated vapor in the presence of non-condensables and showed that the superheating-induced increase of heat transfer was very slight in the condensation of pure vapors (*i.e.* water vapor). Shang and Wang [28] studied the laminar film condensation of a superheated vapor on an isothermal vertical plate and proposed a simple correlation to predict the dimensionless temperature gradient. Winkler et al. [29] concluded that the buoyancy significantly increased the wall shear stress and condensate mass flux in the condensation of R134a. Yang [30] and Hsu [31] developed a one-phase boundary-layer model without considering the effect of buoyancy, which may have a significant effect on the superheated vapor film condensation, especially for the natural convection film condensation.

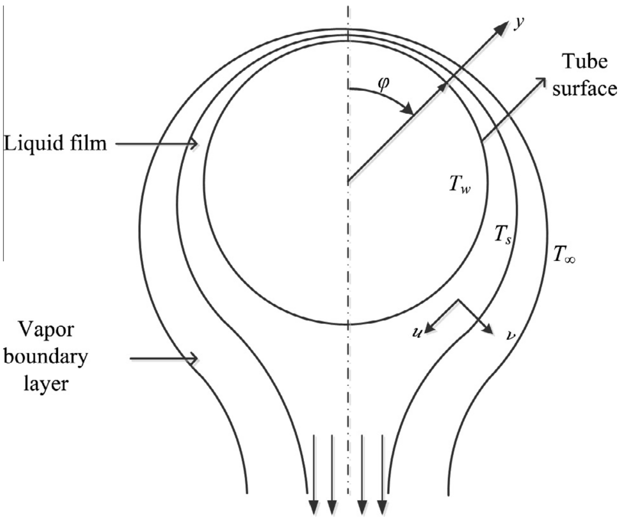

Fig. 1. Physical model and coordinate system. The tube has a uniform wall temperature T_w, while the temperature of vapor is T_∞.

The air condensation in AHCV is a typical film condensation of highly superheated vapor. To our knowledge, cryogenic vapors, *e.g.* air, were not involved in the previous studies, which mainly focused on the water vapor. Because of the differences in the thermophysical properties and working conditions between air and water vapor, distinctive condensation characteristics may inevitably exist. Thus, it is necessary to study the mechanism and characteristics of air condensation both from the theoretical and engineering points of view.

In the present work, a mathematical model of air condensation on a horizontal tube is developed to predict the natural convection film condensation heat transfer characteristics. The effect of superheating, subcooling and buoyancy are discussed for the condensation of air as well as the other vapors, *e.g.* H_2O, R134a, CH_4 and Ar. The obtained results not only help understand the film condensation phenomenon for air and the other superheated vapors, but also provide meaningful guides for the design of AHCV.

2. Numerical system

2.1. Physical model

Fig. 1 displays a schematic illustration of the physical model and the coordinate system. A horizontal tube with a constant wall temperature T_w is surrounded by a large volume of quiescent superheated vapor with a temperature T_∞ (higher than the saturated temperature T_s). Because $T_s > T_w$, the superheated vapor condensates and thus a continuous film appears outside the tube driven by the gravity and the interfacial shear. The buoyancy is particularly taken into account for modeling the laminar film condensation, since the flow and heat transfer processes in the liquid film are affected by the buoyancy in the vapor boundary layer. The assumptions employed in the process of numerical analysis are as follows:

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