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Experimental study of air accumulation in vapor condensation across horizontal tube

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ABSTRACT

In this study, air accumulation in vapor condensation across a horizontal tube was investigated experimentally. A total of 16 thermistors were mounted uniformly on the horizontal tube wall along the circumference of $z = 0.17$ m and $z = 0.63$ m to measure wall temperature. Results show that vapor exists as a three-dimensional diffusion flow and air is carried by vapor toward the downstream at $\theta = 135°$–$225°$ and $z = 0$–0.6 m, and forms a saturated moist air region there, whereas another region is full of moist vapor. A vapor flowing front lies at the joint of two regions, where interdiffusion between vapor and air is in dynamic equilibrium. In the saturated moist air region, the ratio of gas film layer to overall thermal resistance is within the range of 0.92–0.97, the air mole fraction on the gas–liquid interface is within the range of 0.75–0.87, and the heat transfer coefficient at the condensation side is less than 300 W m^{-2} K^{-1}. An increase in cooling water mass flux pushes the vapor flowing front forward, expanding the moist vapor region, ultimately enlarging the vapor condensation area. The present experimental results were compared with the results of the works of Zhou and Rose (1996), Sherkriladze and Gomelauri (1966), Rose (1984), Fujii et al. (1972), Memory et al. (1993), and Chen and Lin (2009). The wall temperature distribution and $\overline{Nu}/Re_l^{0.5}$ variation are reasonable.

1. Introduction

Tube-in-tube condensers have been widely applied in the industrial fields, such as power production, chemical industry, and refrigeration and air conditioning. In a tube-in-tube condenser, cooling water often flows in the tube, whereas vapor flows through the annular tube and condenses over the tube. A universal phenomenon that vapor with noncondensable gas (NCG) condenses over a horizontal tube always occurs. As vapor condenses, NCG accumulates in the condensation section. NCG has two sources, namely, (1) residual air after the condensers are evacuated and (2) hydrogen generated by the chemical reaction between the pipe material and the working fluid. NCG is not released or is only discharged for an indeterminate period because the tube-in-tube condensers are closed during the run. Therefore, the accumulation of NCG in tube-in-tube condensers is common.

NCG is one of the main factors affecting condenser performance and lifetime [1,2]. For example, as hydrogen pressure increases, a lithium bromide absorption condenser needs a larger NTU (number of transfer unit) to obtain the same effectiveness [3]. NCG would also increase the temperature drop of the condensation section in the radically rotating miniature high-temperature heat pipe heat exchanger [4], occupy the condensation section of wicked heat pipes, and reduce the cooling rate [5]. The effect of NCG is notable for a small heat load or a low temperature [6,7], which prolongs the start-up time and causes the temperature oscillation phenomenon and operation failure. More seriously, NCG elevates the operating temperature of a miniature heat pipe, decreases the fluctuation of wall temperature in the adiabatic section, and prevents condensation [8].

NCG adversely affects condensation heat transfer. A mass fraction of air equal to 0.5% causes a reduction in the heat transfer of 50% in the analytical investigation of laminar film condensation on an isothermal vertical plate because NCG is carried by vapor to the gas–liquid interface, which increases the condensation resistance of vapor on the condensate [9]. Many researchers have conducted the experimental and theoretical investigations on vapor condensation with NCG in or on a tube [10–22]. In these investigations, vapor and NCG flow through the condensation section with an exhaust of NCG at all times. In internal flow and condensation, the increase in NCG reduces the condensation heat transfer coefficient and condensation tube wall temperature, but improves the

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Nomenclature

d_o	outer diameter of condensation tube, m
d_i	inner diameter of condensation tube, m
d_v	inner diameter of vapor tube, m
D_{v-a}	diffusion coefficients, m s^{-2}
F	$\frac{gD\mu_l h_{fg}}{u_f \lambda_l (t_f - t_w)}$
f	resistance coefficient
G	mass flux, kg s^{-1}
g	gravity acceleration
h	heat transfer coefficient, W m^{-2} K^{-1}
h_c	convective heat transfer coefficient of cooling water, W m^{-2} K^{-1}
h_g	heat transfer coefficient of gas film layer, W m^{-2} K^{-1}
h_l	condensation heat transfer coefficient of condensate, W m^{-2} K^{-1}
h_{fg}	latent heat, kJ kg^{-1} K^{-1}
h_m	mass transfer coefficient, m s^{-1}
l	tube length, m
M	molecular weight, kg mol^{-1}
$\overline{Nu}$	average Nusselt number = $c_p\mu_c/\lambda_c$
p	pressure, MPa
$p_{s,i}$	vapor saturated pressure on the gas-liquid interface, MPa
Pr_c	Prandtl number of cooling water = $c_p\mu_c/\lambda_c$
Q	power of evaporator, W
q	heat flux, W m^{-2}
R	thermal resistance, °C W^{-1}
R_{gm}	gas constant of mixed gas, kJ kg^{-1} K^{-1}
R_{gv}	gas constant of vapor, kJ kg^{-1} K^{-1}
R_{ga}	gas constant of air, kJ kg^{-1} K^{-1}
Re_l	Reynolds number = $u_f D\rho_l/\mu_l$
Sc	Schmitt number = $\mu/D\rho$
Sh	Sherwood number = $h_c L/\lambda_c$
$\overline{\nabla T}$	average temperature difference across condensate film, °C
t	temperature, °C
t_f	temperature at the vapor inlet, °C
u	velocity of mixed gas, m s^{-1}
x_a	air mole fraction at the vapor inlet
$x_{a,i}$	air mole fraction on the gas-liquid interface

Subscript

α	air
c	cooling water
l	condensate
g	gas film layer
i	gas-liquid interface
m	mean
v	vapor
w	wall
s	saturated

Greek letters

δ	thickness, m
λ	conductivity coefficients, W m^{-1} K^{-1}
μ	dynamic viscosity coefficients, Pa s
θ	circumferential angles of the horizontal tube, °
γ	ratio of the gas film layer to the overall thermal resistance
ρ	density, kg m^{-3}

vapor condensation length [10,11]. NCG also affects the gas-liquid two-phase condensation flow pattern in horizontal and inclined tubes [12,13]. In condensation heat transfer over a horizontal tube bundle, NCG mainly affected the tube row having a lower condensation heat transfer coefficient [14,16]. Changing the tube shape can improve condensation heat transfer, with an equiangular spiral tube having a higher condensation heat transfer coefficient than a circular tube, whereas a drop-shaped tube having a condensation heat transfer coefficient higher by 3% than a circular tube [17]. Condensation heat transfer of vapor with air is affected by multiple factors over horizontal and vertical tubes [18–20], such as the mixed gas Reynolds number, NCG mole fraction, and tube wall temperature. Three types of methods, namely, degradation factor, heat and mass analogy, and two-phase boundary layer, are applied to analyze the effects of NCG on condensation heat transfer quantitatively [21–26]. The degradation factor method determines the decrease in condensation heat transfer coefficient of NCG compared with the condensation heat transfer coefficient of pure vapor [21]. In the heat and mass analogy method, the condensation heat transfer coefficient of NCG may be evaluated at different flow parameters [22]. The distribution of NCG and other heat transfer parameters in the boundary layer is determined using the two-phase boundary layer method by establishing the mass, momentum, and energy conservation equations [23–26].

However, when vapor and NCG are in a closed system, NCG is not released and is detained in the condensation section. For the counterflowing vapor condensation with helium and oxygen in a top-closed bend, helium and oxygen are detained in the condenser top and diffuse to the bottom along the axis [27]. Wang et al. [28,29] experimentally and theoretically investigated the two-dimensional diffusion flow of stagnant air in vertical and inclined tubes and determined that air accumulates at the bottom of the tubes. In summary, the aforementioned studies mainly focus on the case in which the NCG passes through the condensation space. However, only few studies are devoted to the case in which the NCG is detained in the condensation section. Furthermore, few studies investigate the dynamic change in the stagnant NCG and the effect of this change on vapor flow. In the present work, an experiment on vapor condensation with air across a horizontal tube was conducted. Moreover, air accumulation in the condensation section and the effects of air on vapor diffusion flowing were analyzed. Once the position of a large amount of NCG accumulation is obtained, a reservoir can be mounted in such a position to store NCG. Meanwhile, the NCG may be discharged from this position. Meanwhile, NCG may be discharged from there. Therefore, this investigation is helpful to determine the optimal positions for discharging NCG or installation locations of reservoir to reduce the adverse effects of NCG on condensation heat transfer.

2. Experiment

2.1. Experimental facility

Fig. 1 shows the experimental device of condensation heat transfer with air accumulation, which consists of an evaporator and a horizontal tube-in-tube condenser. The evaporator is a cylindrical stainless steel tube, with an outer diameter of 0.436 m, a length of 0.8 m, and a thickness of 0.008 m. Both ends of the evaporator are sealed with a flange. A booster pump is connected to a feedwater tube that is mounted on the right side of the evaporator