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Study on high-speed condensation heat transfer of steam/nitrogen mixture in horizontal rectangular channel

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ABSTRACT

In this paper, the steam condensation mixed with nitrogen is experimentally investigated to examine the effect of non-condensable gas on the steam condensation process at high speed. The mass flux of steam/nitrogen mixture is in the range of 159.2–464.6 kg/(m^2·s), the nitrogen mass fraction is up to 10%, and the inlet pressure ranges between 0.15 and 0.47 MPa. The mass flow rate of cooling water varies from 300 to 900 kg/h. The effects of mass flow rate of cooling water, nitrogen mass fraction, mass flux of steam/nitrogen mixture and channel configuration are studied. It is found that the increase of mass flux of mixture increases the condensation heat flux, the condensation heat transfer coefficient and the overall heat transfer coefficient. Including the nitrogen into steam deteriorates the condensation process, but the influence of nitrogen on the condensation process at high speed is much smaller compared to that at low speed. The increase of mass flow rate of cooling water promotes the condensation heat flux and the overall heat transfer coefficient, but decreases the local condensation heat transfer coefficient. The channel configuration and the gravity has little effect on the high-speed condensation. Finally, a new fitting correlation is proposed to predict the high-speed steam condensation in the presence of nitrogen based on Shah's correlation.

1. Introduction

Condenser is widely used in many industrial applications such as power plants, chemical engineering, and aerospace since it can provide very high heat transfer efficiency and relative constant temperature control. However, the steam condensation inside condensers is a complex phase-change heat transfer process and affected by many factors. Moreover, in many real industrial applications, the non-condensable gas like air easily permeates the steam and thus makes the process more complicated. Therefore, much work has been performed to examine the heat transfer performance of steam condensation in the presence of non-condensable gas. Othmer [1] experimentally investigated the condensation of steam mixed with air inside a horizontal channel. It indicated that as the air mass fraction inside the steam rose from 0 to 0.5%, the average condensation heat transfer coefficient (HTC) decreased by 50%. Lee and Rose [2] carried out experiments to study the film condensation of steam and R113 in the presence of air and hydrogen in a horizontal channel. The measured results perfectly matched the predicted results [3] based on the boundary theory. Al-Shammari et al. [4] found that the main thermal resistance appeared on the steam side, and the thermal resistance dramatically enlarged when the non-condensable gas was involved. Yi et al. [5] established a steady three-dimensional numerical model based on volume of fluid (VOF) method to examine the laminar film condensation of steam with and without non-condensable gas. The result showed that reducing the thermal conductivity of non-condensable gas had a stronger negative effect on heat flux. Yi et al. [6] also found that the effect of some cross-sectional shapes on condensation heat transfer with non-condensable gas was different compared to that without non-condensable gas. Yang et al. [7] found that the effect of air on the direct contact condensation of subcooled water flow under unstable state was larger than that under stable state. Jige et al. [8] conducted an experiment to study the condensation heat transfer of refrigerants without non-condensable gas in a horizontal multiport tube with rectangular minichannels at high mass flux. Bespalov et al. [9] performed a condensation experiment on steam-air mixture in horizontal rectangular channels at low speed ranged from 1.8 to 3.7 m/s, and the result showed the dependences of heat transfer coefficient with the initial moisture mass fraction and mixture flow rate. Lee and Kim [10] discovered that the non-condensable gas had little effect on the steam condensation in small-diameter condenser tubes. Then, Lee and Kim [11] developed new correlation for the condensation heat transfer coefficient inside a vertical tube regardless of tube diameter in the presence of non-condensable gas. Milman et al. [12] investigated the influence of coolant flow

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Nomenclature

A	area, m^2
c_p	specific heat capacity, kJ/(kg·K)
d	hydraulic diameter, m
f	Darcy friction factor
G	mass flow rate, kg/h
H	specific enthalpy, kJ/kg
h	heat transfer coefficient, kW/(m^2·K)
K	overall heat transfer coefficient, kW/(m^2·K)
l	length, m
M	mass flux, kg/(m^2·s)
Nu	Nusselt number
Pr	Prandtl number
p	pressure, kPa
Q	heat transfer rate, kW
q	heat flux, kW/m^2
Re	Reynolds number
T	temperature, °C
u	velocity, m/s
W	nitrogen mass fraction
x	steam quality

Greek symbols

δ	wall thickness, m
λ	thermal conductivity of wall, W/(m·K)
ν	kinematic viscosity, m/s^2
ρ	density, kg/m^3

Subscripts

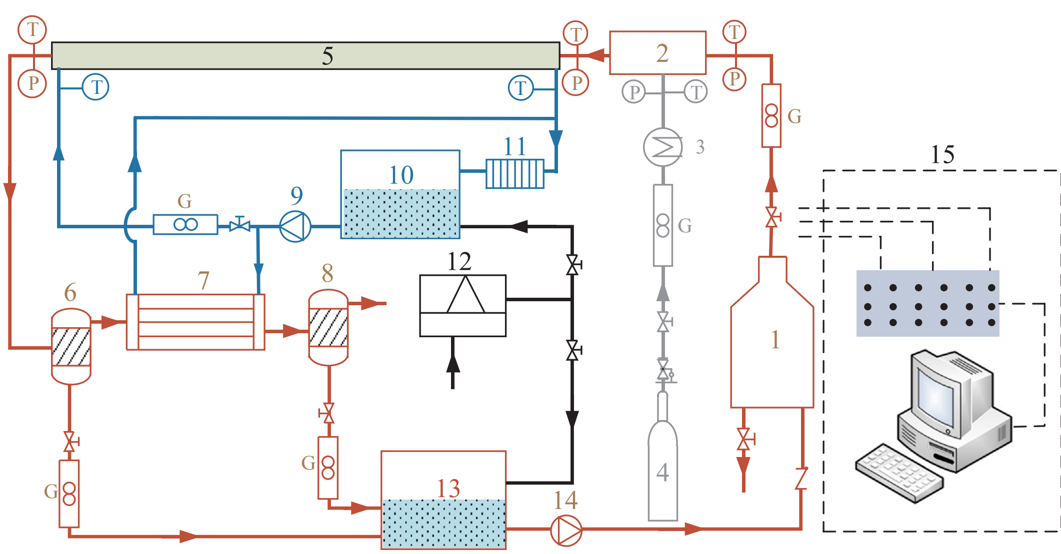
in	inlet
i	index
out	outlet
s	saturation
v	mixture
w	cooling water
wo	wall on the coolant side
wi	wall on the mixture side

Abbreviation

HTC	heat transfer coefficient

patterns including counter flow, forward flow and cross flow on the steam condensation process in tubes and channels. Kobayashi et al. [13] examined the effect of gravity on the condensation process of heat pipe with non-condensable gas. The result indicated that the gravity and non-condensable gas had significant effect on the location and profile of an interfacial layer. Ren et al. [14] developed a correlation for steam condensation in the presence of non-condensable gas for stratified flow and annular flow, and the deviations between the correlation and experimental data were within 20%. Su et al. [15] proposed empirical correlations for steam condensation mixed with air and helium in a vertical tube external surface. Wu et al. [16] examined the steam condensation in the presence of non-condensable gas in horizontal tubes. The result showed that the heat transfer coefficients on the tube top were much larger than those at the bottom. Ma et al. [17] observed intermittent annular flow during the steam condensation process in the presence of non-condensable gas in trapezoidal microchannels.

In the aforementioned studies, the inlet velocities of mixture are usually very small, most of them are smaller than 100 m/s. However, in the start, stop and low-load operating conditions, the high pressure and high temperature steam in the ship steam power system is usually released to a low pressure condenser after cooling and decompressing. In these situations, the inlet velocity of condenser could be larger than 200 m/s. To the best of our knowledge, there are limited open literatures to study the condensation heat transfer of steam with non-condensable gas at such a high speed. In our previous study, the steam condensation was examined at large steam mass flux and non-condensable gas mass fraction, in which the steam mass flux varied from 203.7 to 431.1 kg/(m^2·s), and the nitrogen mass fraction varied from 0% to 15%. It was interesting to find that the effect of nitrogen on the condensation was small at the large steam mass flux. However, due to the low thermal conductivity of steel channel and short channel length, the steam quality of outlet flow was larger than 0.814, which was far



1. Electronic boiler 2.Mixer 3. Pre-heater 4.Nitrogen cylinder 5. Test section 6. Separator 7. Post-Condenser 8. Separator 9. Pump 10. Water tank 11. Coolant cooler 12. Water softener 13. Water tank 14. Pump 15.Data acquisition G: Mass flowmeter T: Temperature P: Pressure

Fig. 1. Schematic diagram of experimental system.