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Condensation heat transfer characteristic of high-speed steam/nitrogen mixture in horizontal rectangular channel

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ABSTRACT

Steam condensation in the presence of nitrogen is experimentally performed in a horizontal rectangular channel with cross sectional dimension of 5 × 6 mm. Steam mass flux varies from 203.7 to 431.3 kg m^{-2} s^{-1}, while the nitrogen mass fraction from is 0% to 15%. Coolant water flows countercurrent in a rectangular channel as well, which is the same size with the steam side. The steam channel is on top of the coolant channel, and the released heat from the steam is transferred to the coolant water by heat conduction only through the connecting part of each channel, the thickness of which is 3 mm. The coolant mass flow rate is from 500 to 1100 kg h^{-1}, while the corresponding coolant side Reynolds number is from 2.2×10^4 to 5.1×10^4 and the coolant side heat transfer coefficient is from 20.2 to 40.1 kW m^{-2} K^{-1}. The results show that higher coolant Reynolds number results in significant promotion of the overall heat transfer coefficient, while the condensation heat transfer coefficient is reduced. In addition, larger steam mass flux leads to greater overall heat transfer coefficient and condensation heat transfer coefficient. However, the influence of nitrogen on condensation is not significant, especially for condensation with higher steam mass flux.

1. Introduction

Condensation has been a popular heat transfer process in industrial applications, such as automotive condensers, air conditioning and nuclear plant. Therefore, the analysis of condensation process is of great importance during the design of heat exchangers. A transformation from vapor to liquid is involved in condensation accompanied with high heat transfer rate. However, the existence of non-condensable gas (NCG) is found to induce severely negative effect on condensation, even with a small mass fraction [1]. This fact has led to a large amount of studies on overall understanding of condensation with NCG.

In recent years, lots of experiments on condensation in the presence of NCG were carried out under various heat transfer surfaces, condensation patterns and NCG mass fractions [2–12]. Ren et al. [2] conducted an experimental investigation on condensation of steam in the presence of air in a horizontal tube. It was shown that the overall heat transfer coefficient (HTC) decreased with higher inlet NCG mass fraction and increased with higher inlet mass flux and inlet pressure. Two correlations for HTC were proposed for stratified flow and annular flow regimes, respectively, in which the modified Froude number was selected as the transition criteria from stratified to annular flow. Su et al. [3] experimentally studied the effect of NCG on steam heat removal capacity over a vertical tube external surface, in which air and helium were designated as the NCG, respectively. It was found that the decrease of HTC was sharper compared with that predicted by the Nusselt analysis. Two empirical correlations for the HTC were proposed for the air experiments and helium experiments, respectively. The average relative deviation between the steam/air correlation and experimental results was 10%, while it was 20% for the steam/helium correlation. Chantana and Kumar [4] performed both experimental and theoretical research of steam/air condensation in annulus vertical tube with high inlet air fraction. Waviness at the interface was observed at high gas mixture Reynolds number. The condensation HTC increased sharply with higher Reynolds number and inlet water vapor mass fraction, while rough and suction effect was proved to enhance the heat transfer rate at low inlet vapor mass fraction according to the comparison between the model results and experimental results. A correlation was also proposed for the condensation HTC through the heat and mass analogy model. Ma et al. [7] studied the effect of NCG concentration, saturation pressure and surface sub-cooling degree on the HTC of dropwise condensation on a vertical plate. The experimental results showed that the heat and mass transfer

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Nomenclature

A	area, m^2
c_p	specific heat capacity, kJ kg K^{-1}
d	characteristic dimension, m
G	mass flux, kg m^{-2} s^{-1}
m	coolant mass flow rate, kg h^{-1}
h	heat transfer coefficient, kW m^{-2} K^{-1}
i_0	specific enthalpy of steam at the inlet, kJ kg^{-1}
i_1	specific enthalpy of condensate at the outlet, kJ kg^{-1}
i_2	specific enthalpy of un-condensed steam at the outlet, kJ kg^{-1}
$i_{n,0}$	specific enthalpy of nitrogen at the inlet, kJ kg^{-1}
$i_{n,1}$	specific enthalpy of nitrogen at the outlet, kJ kg^{-1}
K	overall heat transfer coefficient, kW m^{-2} K^{-1}
M_0	steam mass flow rate at the inlet, kg s^{-1}
M_1	condensate mass flow rate at the outlet, kg s^{-1}
M_2	un-condensed steam mass flow rate at the outlet, kg s^{-1}
M_n	nitrogen mass flow rate, kg s^{-1}
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
$\overline{T}$	average temperature, °C
u	velocity, m s^{-1}

Greek symbols

δ	wall thickness, m
η	thermal equilibrium index
ε	mass equilibrium index
λ	thermal conductivity of wall, W m^{-1} K^{-1}
ν	kinematic viscosity, m s^{-2}
ρ	density, kg m^{-3}

Subscripts

in	inlet
i	index
n	nitrogen
s	saturation
V	vapor
w	coolant water side
wo	wall at the coolant side
wi	wall at the mixture side

Superscripts

$'$	first measuring point of temperature
$''$	last measuring point of temperature

Abbreviation

HTC	heat transfer coefficient
NCG	non-condensable gas

during the dropwise condensation with NCG was more intense compared with that during the filmwise condensation.

As for the numerical simulation of condensation with NCG, the main approach is to solve the governing equations of each phase directly based on several assumptions or empirical correlations [13–17]. Li [13] developed a program of computational fluid dynamics (CFD) for condensation of turbulent flows in the presence of NCG in a vertical cylindrical condenser tube. The code was able to simultaneously solve the condensation flows involving multispecies of gas and liquid in both vapor side and cold side, which was a disadvantage of the current available commercial package for CFD simulation. The simulation results agreed well with the tested data and it was demonstrated that the heat flux distribution along the condenser tube could not be regarded as a simple polynomial curve fit. Tang et al. [14] numerically investigated the condensation heat transfer performance of steam in the presence of air outside a horizontal tube utilizing the double boundary layer model. Coupled heat and mass transfer was solved with the finite difference method, and the variations of NCG mass concentration, velocity and temperature were analyzed. The increase of mass concentration of NCG from the bulk to the interface led to a significant reduction in HTC, even with a low mass concentration of NCG in the bulk mixture. In addition to solving the governing equations, methods using heat and mass transfer analogy, heat and momentum balance have also been effective ways in evaluating condensation in the presence of NCG [18–21]. Heat and mass transfer analogy was adopted by Caruso and Di Maio [18] to numerically simulate the heat and mass transfer at the liquid/gas interface of condensation inside inclined tubes. Suction effect was emphasized because of its obvious impact on temperature and concentration profiles and corresponding HTC. A set of differential and algebraic equations representing the heat and mass transfer process of condensation with NCG in both the vapor side and the coolant side of a vertical condenser tube was solved by a computer program in MATLAB [19]. The results indicated that a well modeling of the heat transfer process in the coolant side and inside the wall was demanded in order to obtain a satisfactory agreement between the simulation results and the experimental results.

Although much literature has presented studies on condensation with NCG, the heat transfer characteristic of high-speed steam condensation in the presence of NCG is seldom reported. In addition, steam condensation with NCG in non-circular channel is relatively insufficient. Therefore, an experimental investigation of steam/nitrogen condensation inside a horizontal rectangular channel is performed in the present study.

2. Experimental investigation

2.1. Experimental facility

As shown in Fig. 1, the experimental system consists of three primary sections, which are the steam loop, the coolant loop and the NCG loop. The steam is generated from the evaporator, which is an electronic boiler with rated power of 45 kW. There is a one-to-one correspondence between the operating pressure and steam mass flow rate of the electronic boiler, while the maximum mass flow rate and pressure of the generated steam are 65 kg/h and 0.7 MPa, respectively. Nitrogen is chosen as the NCG in the present test, produced by a nitrogen cylinder with high pressure. Saturated steam from the evaporator remains its saturation temperature at a certain pressure, while the nitrogen is pre-heated to get the same temperature. The maximum power of the nitrogen pre-heater is 18 kW. The pressure of nitrogen is set the same as the pressure of steam as well. Before the nitrogen is heated to demanded temperature, it is discharged into the atmosphere instead of flowing