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Experimental study on the effect of wall-subcooling on condensation heat transfer in the presence of noncondensable gases in a horizontal tube

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ABSTRACT

For the purpose of analyzing the influence of wall sub-cooling on condensation heat transfer characteristic in the presence of noncondensable gases inside a horizontal tube, experiments for air-cooling and water-cooling at the secondary side outside the condenser tube have been conducted. By comparing the experimental data of different inlet air mass fractions, mixture gases velocities and coolant volume flow rates, the variation of local heat transfer coefficients with wall sub-cooling was obtained. The results show that for annular and wavy flow, the condensation heat transfer coefficient increases with the increasing wall sub-cooling but decreases for stratified flow. For annular and wavy flow, the positive influence of wall sub-cooling on condensation heat transfer coefficient is enhanced by the rise of inlet noncondensable gas mass fraction, mixture gases velocity and pressure. Finally, the modified correlations respectively for annular-wavy flow and stratified flow have been proposed which show a good agreement with the experimental data.

1. Introduction

Condensation of steam has been widely used in many industrial applications, including refrigeration systems, power generation, aerospace industry, and so on. Currently, with the development of safety technology for nuclear systems, the heat transfer of condensation is playing an important role in removing the heat to ensure the safety of nuclear power plant when some severe accidents happen. Since horizontal condensers with in-tube condensation of steam have a higher capability of heat removal and compression resistance compared with vertical heat exchangers, many nuclear safety systems have introduced this kind of heat exchangers into the designs for some engineered safety features of nuclear power plants, such as the passive containment cooling system (PCCS) in ABWR-II, residual heat removal system in AC600 and SWR1000 and passive auxiliary feedwater system in APR+. But, different with conventional applications, there is always noncondensable gases existing in the heat exchangers which severely influences the condensation heat transfer characteristic and brings inconvenience to the analysis of thermal–hydraulic behaviors for these heat exchangers.

Unlike vertical tubes, the condensation heat transfer process is more complicated inside horizontal tubes since the radial distribution of the condensate film is non-uniform caused by gravity. The variability of flow regimes inside the tubes makes it difficult to study the characteristic of condensation heat transfer. For this reason, few investigations on condensation inside a horizontal tube have been conducted so far.

Chato (1962) concentrated on laminar flow condensation and separated the heat transfer process into two parts: the upper portion of the tube where falling-film condensation existed and the bottom portion where convective heat transfer of the condensate occurred. Rosson and Meyers (1965) measured the local heat transfer coefficient with different angles around the tube and found that heat transfer coefficient continuously decreased from the top to the bottom of the tube. Cavallini and Zecchin (1974) used the results of theoretical regression analysis to define a two-phase multiplier which was applied to their dimensionless equation for annular flow. Jaster and Kosky (1976) studied the condensation heat transfer in a mixed flow regime and proposed a correlation similar with Nusselt's pioneering analysis. Saha (1979) collected a wide range of experimental data from other researchers and developed an empirical correlation for annular flow. According to his study, the mechanisms of condensation and evaporation were similar in the absence of nucleate boiling. With this idea, he set out to modify the convective component of his flow boiling

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Nomenclature

$c_{p,c}$	specific heat capacity at constant pressure, J/(kg K)
D	tube diameter, m
h_i	heat transfer coefficient, W/(m^2 K)
j	superficial velocity, m/s
j^+	dimensionless velocity
Ja	Jakob number
L	length, m
M	mass flow rate, kg/s
Nu	Nusselt number
P	pressure, MPa
P_{sred}	reduced pressure
q	heat flux, W/m^2
Q	heat transfer rate, W
Re	Reynolds number
Δt	wall sub-cooling, K
T	temperature, K
u	mixture gases velocity, m/s
V	volume flow rate, m^3/h
w	noncondensable gas mass fraction

Greek letters

λ	thermal conductivity, W/(m K)
ρ	density, kg/m^3

Subscripts

a	air
c	coolant
cal	calculated results
exp	experimental results
g	gas
in	inlet
l	liquid
m	mixture gases
out	outlet
s	steam
w	wall
W	water
wi	inner wall
wo	outer wall

correlation for use during condensation. Tang et al. (1997) developed a new two-phase multiplier correlation valid in annular flow based on his experimental results with the mixture gases mass velocities being larger than 300 kg/(m^2 s) and the reduced pressure ranging from 0.2 to 0.53. Dobson and Chato (1998) conducted an experimental study on heat transfer and flow regimes during the condensation of refrigerants in horizontal tubes with the tube diameters ranging from 3.14 mm to 7.04 mm. Based on the experimental data, they divided various flow regimes into two broad categories of gravity-dominant and shear-dominated flows and proposed the heat transfer correlations for each of these two flow regimes. Thome et al. (2003) put forward a new general flow pattern based the heat transfer model for condensation in horizontal tubes with considering the effect of interfacial roughness of the liquid–vapor on heat transfer. Kondo and Nakamura (2006) performed experiments using a horizontal condenser in the PCCS and finally estimated its thermal–hydraulic behavior, condensate distribution and hydraulic stability.

Compared with the investigations of pure steam condensation in horizontal tubes, very few works have been reported on the condensation heat transfer characteristics with noncondensable gases inside. Sideman et al. (1977) conducted the in-tube condensation experiments in the presence of noncondensable gases at low driving forces and the results indicated that the heat transfer coefficients could go down by 65% with a 3% air outlet concentration in steam. Nakamura (Arai and Nakamura, 2002) measured the cross-section averaged heat transfer coefficient through the experiments of steam/air mixture condensation in a horizontal U-tube under typical PCCS operation conditions. Huhtiniemi and Corradini (1993) performed an experimental investigation in a rectangular flow-channel over a condensing aluminum surface. Lee and Kim (2011) proposed a theoretical model for steam condensation with noncondensable gases using heat and mass analogy and developed an empirical correlation based on their previous works for vertical tubes (Lee and Kim, 2008). Caruso et al. (2013a, 2013b, 2014) applied heat and mass transfer analogy to condensation in the presence of noncondensable gases inside inclined tubes and the calculated Nusselt number showed a good agreement with the experimental results. Wu and Vierow (2006) showed the experiments of condensation in the presence of air inside a horizontal tube. The temperature gradient across the tube wall and the heat transfer coefficients at the top and bottom of the tube were obtained locally which gave help to have a better understanding on the condensation phenomena. Ren et al. (2014, 2015) experimentally studied the characteristics of condensation heat transfer and developed a theoretical model based on Liao's modified diffusion layer theory including the roughness and suction effect.

It is well known that wall sub-cooling is an important element deciding the heat transfer coefficient for condensation. According to the theoretical model proposed by Nusselt (1916), the heat transfer coefficient for pure steam condensation decreases with the increase of the wall sub-cooling. When the temperature difference between the bulk steam and wall gets bigger, more steam will be condensed which causes the condensate film thicker. Since the thermal resistance for condensation is strongly influenced by the capacity of heat conduction through the film, the increase of film thickness finally restrains condensation heat transfer process. However, with noncondensable gases inside, the major thermal resistance for condensation will transform from the film to noncondensable gas layer at the liquid–gas interface when the thickness of this gas layer reaches certain value. Under this situation, the previous conclusion for the effect of wall sub-cooling on pure steam condensation may not be applicable. But very few works consider the influence of wall sub-cooling on condensation in the presence of noncondensable gases and there is still not an acknowledged conclusion how the wall sub-cooling affects the heat transfer coefficient so far.

Uchida et al. (1964) performed the experiments of steam/air condensation on the outside wall of a vertical tube for different water flow rates inside the tube. A similar result for the effect of wall sub-cooling on heat transfer coefficient was found like Nusselt's conclusion. Dehbi et al. (1991) conducted an experimental and theoretical investigation to analyze the influence of noncondensable gas on steam condensation under free convection condition. A correlation was proposed which showed the average heat transfer coefficient was in inverse proportion to 2.5th power of wall sub-cooling. Hasanein et al. (1996) investigated the condensation inside a vertical tube and developed an empirical correlation which indicated wall sub-cooling played a negative role on condensation. Liu et al. (2000) conducted a set of condensation experiments outside a vertical tube while the water inside the tube was boiling. Based on his experimental data, heat transfer coefficient