International Journal of Heat and Mass Transfer 104 (2017) 1110–1119

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Forced convection condensation of steam in the presence of multicomponent noncondensable gases inside a horizontal tube

Huiqiang Xu, Haifeng Gu *, Zhongning Sun

Fundamental Science on Nuclear Safety and Simulation Technology Laboratory, Harbin Engineering University, Harbin 150001, China

ARTICLE INFO

Article history:
Received 22 June 2016
Received in revised form 9 September 2016
Accepted 12 September 2016

Keywords:
Condensation
Multicomponent noncondensable gases
Horizontal tubes
Heat transfer correlation

ABSTRACT

An experimental investigation on condensation heat transfer characteristics of steam in the presence of multicomponent noncondensable gases in a horizontal tube is conducted in the present research. The experimental runs are carried out at a volume ratio of helium and noncondensable gases varying from 0% to 90%, the mixture gases pressure between 0.13 and 0.2 MPa, over the mixture gases velocity changing from 8 to 34 m/s, covering all the major flow patterns inside a pipe. The effects of inner wall subcooling, mixture gases velocity and pressure on local heat transfer coefficient have been analyzed for annular, wavy and stratified flow. The change of the condensation heat transfer capacity for different volume ratios of helium in the noncondensable gases have been studied at the same time. The results indicate that the local heat transfer coefficient increases with the increasing wall subcooling for annular and wavy flow but decreases for stratified flow. With the flow regime transforming from annular to stratified flow, the active influence of the gases velocity is gradually weakened and the local heat transfer coefficient even starts to decrease when it reaches stratified flow. For all flow patterns, the increases of helium volume fraction and mixture gases pressure always enhance the condensation heat transfer. Based on the experimental analysis, an empirical correlation for predicting the local heat transfer coefficient is proposed. The comparison of the calculated results and the experimental data shows that the present correlation can give satisfactory engineering accuracy.

1. Introduction

As a symbolic component of new Generation III and IV nuclear power plant, the thermal hydraulic characteristics of the passive containment cooling system (PCCS) has been always getting a lot of attention. Under some accidents happening in nuclear power plants, such as the loss of coolant accident (LOCA) and the main steam line break accident (MSLB), a large amount of steam will be released into the inner space of the containment causing the temperature and pressure rising rapidly which may jeopardize the integrity of the containment. Therefore, the major task of the PCCS is condensing the steam to accomplish the heat removal and decompression and finally preventing the steam with radioactive particles from leaking into the atmosphere. Since horizontal condensers with in-tube condensation of steam have a higher capability of heat transfer and compression resistance compared with traditional vertical heat exchangers, the design of the PCCS in ABWR-II has employed horizontal condensers in order to improve the ability of the whole system. Different from the routine applications of condensation in refrigeration systems, seawater desalination industry, air conditioning and chemical process industry, there is always air mixed with steam inside the PCCS condensers which greatly inhibits the condensation heat transfer process and weaken the heat removal capacity. At a worse condition for LOCA, the zirconium-water reaction between the fuel can and the coolant will happen producing a great deal of hydrogen which may bring an obvious effect to the performance of the condenser. Therefore, an experimental investigation on the heat transfer characteristics of steam with multicomponent noncondensable gases (air and hydrogen) in horizontal tubes is needed to confirm the performance of the condenser designed for the PCCS. Considering the risk of explosion using hydrogen as one component of the noncondebsable gases, most researchers used helium taking the place of hydrogen since the relative molecular weight of hydrogen and helium are the same and helium is much safer in the experimental application.

Many researchers have put efforts to explore the mechanism of condensation heat transfer in the presence of noncondensable gases so far, especially in vertical downflow. Jiqiang Su [1,2] built an experimental system to analyze the average heat transfer

* Corresponding author.
E-mail addresses: xuhuiqiangheu@163.com (H. Xu), guhaifeng@hrbeu.edu.cn (H. Gu).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2016.09.031

Nomenclature

$c_{p,c}$	specific heat capacity at constant pressure, J/(kg·K)
d	tube diameter, m
D	diffusivity coefficient, m^2/s
h	heat transfer coefficient, $W/(m^2{\cdot}K)$
i_{lg}	enthalpy of vaporization, J/kg
j	superficial velocity, m/s
Ja	Jakob number
L	length, m
m	mass flow rate, kg/s
M	molecular weight
Nu	Nuseelt number
P	pressure, MPa
P_{sred}	reduced pressure
q	heat flux, W/m^2
Re	Reynold number
Δt	wall sub-cooling, K
T	temperature, K
u	mixture gases velocity, m/s
V	volume flow rate, m^3/h
w	mass fraction
X	volume fraction

Greek letters

α	thermal diffusivity, m^2/s
λ	thermal conductivity, W/(m·K)

Subscripts

air	air
b	bulk mixture gases
c	coolant
cal	calculated results
exp	experimental results
f	film
g	gas
He	helium
in	inlet
l	liquid
m	mixture gases
nc	noncondensable gases
s	steam
w	wall
wi	inner wall
wo	outer wall

characteristics of steam with noncondensable gases over a vertical tube external surface. Yi [3] used a high-speed digital camera to capture real-time images of water vapor condensation with noncondensable gas under different wall temperatures and air concentrations. Kuhn et al. [4] investigated experimentally the local heat transfer for the condensation of steam/air/helium mixtures inside a vertical tube. On the basis of his research, three different types of correlations were proposed. Liu [5] conducted a set of condensation experiments outside a vertical tube when the water inside the tube was boiling. Dehbi [6] focused on the effect of noncondensable gases on steam condensation under free convection conditions. A theoretical model based on the conservation boundary equations of mass, momentum and energy was brought out. Siddique [7] studied the forced convection condensation experimentally to predict the steam condensation rate and correlate the local heat transfer coefficient using nondimensional parameters. Hasanein et al. [8] obtained the experimental data over a wide range of parameters inside a vertical tube. The thermal resistances of condensate film and noncondensable gas layer were compared in his research. Lee and Kim [9] conducted the experiments inside a vertical tube with relatively small diameter and a correlation based on dimensionless shear stress was developed finally. Rao [10] tried to solve the problem of laminar film condensation of vapor in the presence of high concentration noncondensable gas such as humid air flowing in a vertical pipe under laminar forced convection conditions theoretically.

Different from condensation on vertical surface, in horizontal tubes, the directions of gravity and the shear force on the condensate film are mutual perpendicular which means the thickness of the film is asymmetry distributed around the inner wall. Therefore, there will be a great difference of the local heat transfer coefficient between the top and bottom inside the tube. At the same time, more two-phase flow regimes besides annular flow which is the only flow pattern existing in vertical tubes will be observed. Due to these differences, the heat transfer process for condensation in horizontal tubes is much more complicated and the corresponding research is more difficult. As a result, few achievements on condensation in the presence of noncondensable gases for horizontal tubes are obtained now. Sideman et al. [11] conducted the in-tube condensation experiments with noncondensable gases at low driving forces and the results showed that the heat transfer coefficients could go down by 65% with a 3% air outlet concentration in steam. Nakamura [12] measured the cross-section averaged heat transfer coefficients through the experiments on steam/air mixture condensation in a horizontal U-tube under typical PCCS operation conditions. Caruso and Vitale [13,14] conducted an experimental study on the average heat transfer coefficients for condensation under different tube internal diameters and inclination conditions. Wu and Vierow [15] showed experiments with condensation in the presence of air inside horizontal tubes. 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 [16,17] investigated the effect of noncondensable gases on condensation heat transfer inside horizontal tubes experimentally. A new correlation for stratified flow was built on the basis of correlation proposed by Jaster and an annular flow correlation was developed using the two-phase multiplier approach by Cavallini. The author [18,19] improved the experimental method and expanded the range of wall sub-cooling and two-phase flow regime for making a further study on condensation mechanism. By analyzing the effect of all kinds of parameters, a correlation for predicting the local heat transfer coefficient for steam/air condensation was ultimately put forward which showed a good agreement with the experimental data.

Although much effort has been devoted to investigating the heat transfer characteristics of condensation in the presence of noncondensable gases, some problems have not been solved yet. First, there is still not a comprehensive and final conclusion about the effect of helium on heat transfer ability. According to Dehbi's research, with more air being replaced by helium, the condensation heat transfer ability will be deteriorated at low air fraction. And in Liu's work, a reduction factor of 20% is suggested when the mole mass fraction ratio of helium to noncondensable gases is less than 30% which means helium has more inhibiting effect on the heat transfer than air. However, in Siddique's investigation,