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Development of a new empirical correlation for steam condensation rates in the presence of air outside vertical smooth tube

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ABSTRACT

In the past several decades, experimentalists have proposed a large number of correlations to estimate steam condensation rates in the presence of noncondensable gases within free convection regime. However, these correlations are in different forms, and even express conflicting dependencies of the condensation coefficient on some parameters. This study is to aim at developing a new correlation which can faithfully reflect the complex dependencies of condensation coefficient on pressure, air mass fraction and wall subcooling. Considering that more measured data can certainly help to analyze the relationship between condensation coefficient and these parameters, total 374 sets of experimental data have been obtained. It is found that there is a negative power function relation between condensation coefficient and wall subcooling, and the exponent varies with wall subcooling and total pressure. The new correlation, covering two orders of magnitude in the condensation heat transfer coefficient, is valid for pressure ranging from 0.2 to 0.5 MPa, air mass fraction ranging from 0.1 to 0.8 and wall subcooling ranging from 10 to 70 °C. Finally, we have made comparison with experimental data obtained by other investigators which shows that the new correlation is applicative for not only steam-air condensation but also steam-nitrogen and steam-argon condensation, and it can be extended to larger scope of engineering applications.

1. Introduction

The condensation phenomenon plays an indispensable role in many fields, such as the chemical and power industry, including nuclear power plants. In the nuclear power plant, when a hypothetical design basis accident (e.g. loss of coolant accident (LOCA) or main steam line break (MSLB)) occurs, large amounts of steam with high pressure and temperature will enter the containment, which is the last of the several barriers to the escape of radioactive species. To ensure the structural integrity of the containment under accident, many advanced nuclear reactor systems have incorporated passive containment cooling system (PCCS) (Kang and Park, 2001; Shiralkar et al., 1993; Arnold et al., 1996). PCCS can remove a majority of decay heat to the outside of the containment during LOCA or MSLB by the steam condensation over specific heat transfer surface. Since the containment is full of air in the normal situation, the steam condensation process will be carried out in the presence of air. The air, as a noncondensable gas, can largely degrade the condensation heat transfer rate (Othmer, 1929; Al Diwani and Rose, 1972; Yin et al., 2016), so scientific and systematic investigation on the steam-air condensation is meaningful and essential for the nuclear safety (Ganguli et al., 2008; Kageyama et al., 1993).

Since the earliest study of steam-air condensation by Othmer (1929), steam condensation in the presence of air has been widely studied by using theoretical and experimental ways (Uchida et al., 1965; Tagami, 1965; Dehbi, 1990; Kataoka et al., 1992; Murase et al., 1993; Liu et al., 2000; Wu and Vierow, 2006; Chantana and Kumar, 2013; Ren et al., 2014; Su et al., 2013, 2014). Especially, plenty of experiments have been performed to determine the overall heat transfer coefficient (HTC) of steam condensation in the presence of air under a variety of conditions. And several empirical correlations for steam condensation rate in the presence of noncondensable gas have been developed (Uchida et al., 1965; Tagami, 1965; Dehbi, 1990; Kataoka et al., 1992; Murase et al., 1993; Liu et al., 2000; Su et al., 2013, 2014). The most notable correlations are listed in Table 1. The first published correlation, also the most extensively used one, is developed by Uchida et al. (1965). In his correlation, the condensation HTC depends only on

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Nomenclature

General symbols

A	area of condensation heat transfer (m^2)
d	tube diameter (m)
G	mass flow rate of the coolant (kg/s)
Gr	Grashof number
H	enthalpy of the cooling water (J/kg)
h	heat transfer coefficient ($W/m^2 \cdot °C$)
L	tube length (m)
M	molar mass (kg/mol)
n	number of molecules
P	pressure (Pa)
Q	heat transfer rate (W)
T	temperature (°C)
W	air mass fraction
I.D.	inner diameter (m)
O.D.	outer diameter (m)
X	mole fraction
ø	correct factor

Subscripts

a	air
b	bulk
c	coolant
cyl	cylinder
flat	flat
in	inlet
out	outlet
s	steam
w	wall

Abbreviation

HTC	heat transfer coefficient
LOCA	loss of coolant
MLSB	main steam line break
PCCS	passive containment cooling system

Table 1
Summary of empirical correlations for steam condensation rate in the presence of air.

Author	Correlation	Experimental conditions
Uchida et al. (1965)	$h = 380\left(\frac{1-W_a}{W_a}\right)^{0.7}$	$0.23 \leqslant W_a \leqslant 0.91$; $0.1 \leqslant P \leqslant 1.8$ MPa; $10 \leqslant \Delta T \leqslant 140$ K; $0.3 \leqslant L \leqslant 0.9$ m
Tagami (1965)	$h = 11.4 + 284\left(\frac{1-W_a}{W_a}\right)$	$0.38 \leqslant W_a \leqslant 0.83$; $T_w = 322$ K; $L = 0.3$ m
Dehbi (1990)	$h = L^{0.05}\Delta T^{-0.25}\{3.7 + 28.7P - (2438 + 458.3P)\lg W_a\}$	$0.28 \leqslant W_a \leqslant 0.9$; $0.15 \leqslant P \leqslant 0.45$ MPa; $10 \leqslant \Delta T \leqslant 50$ K; $0.3 \leqslant L \leqslant 3.5$ m
Kataoka et al. (1992)	$h = 430\left(\frac{1-W_a}{W_a}\right)^{0.8}$	Not available
Murase et al. (1993)	$h = 470\left(\frac{1-W_a}{W_a}\right)$	$0.44 \leqslant W_a \leqslant 0.97$; $0.1 \leqslant P \leqslant 0.35$ MPa; $295 \leqslant T_b \leqslant 383$ K; $0.9 \leqslant L \leqslant 4.2$ m
Liu et al. (2000)	$h = 55.635X_s^{2.344}P^{0.252}\Delta T^{0.307}$	$0.395 \leqslant X_s \leqslant 0.873$; $0.25 \leqslant P \leqslant 0.46$ MPa; $4 \leqslant \Delta T \leqslant 25$ K
Su et al. (2013)	$h = \Delta T^{-0.6}\{10189.3 + 90416.4P - (4314.4 + 46537P)\log(100W_a)\}$	$0.2 \leqslant W_a \leqslant 0.8$; $0.2 \leqslant P \leqslant 0.6$ MPa; $27 \leqslant \Delta T \leqslant 70$ K
Su et al. (2014)	$h = \Delta T^{-0.35}\{-2913.62 + 7957.3P - (7841.62 + 3051.85P)\log W_a\}$	$0.07 \leqslant W_a \leqslant 0.52$; $0.4 \leqslant P \leqslant 0.6$ MPa; $13 \leqslant \Delta T \leqslant 25$ K

the air mass fraction, while other relevant parameters, such as pressure and wall subcooling, have not been taken into consideration. This is mainly due to the method by which the experiment is conducted. The experiment is started with a vessel filled with non-condensable gases (air, nitrogen or argon) at 0.1 MPa and 293 K, and the condenser wall temperature is hold constantly at 322 K. During the experiment, they progressively add steam while keeping unchanged the original air mass content. Hence, Uchida's experiment is characterized by a constant noncondensable gas density. Thereafter, Tagami (Tagami, 1965) have performed a similar experiment using the same facility, and similar tests are also conducted by Kataoka (Kataoka et al., 1992) and Murase (Murase et al., 1993). Since the experiment methods are similar to that of Uchida's, they have correlated the HTCs as the Uchida's correlation. In consideration of the absence of some important variables, these simple correlations are not available in many situations.

Unlike the previous correlations, Dehbi (1990) proposed a new correlation which includes not only the air mass fractions, but also the total pressure, wall subcooling and tube length. Then, Liu et al. (2000) formulated their own correlation for heat exchanger design and post-accident containment analysis which also takes air mass fractions, pressure and wall subcooling into consideration. Most recently, Su et al. (2013, 2014) proposed two correlations which are similar to Dehbi's. These four correlations all contain the main thermal-hydraulic parameters, but the forms of each correlation are quite different from each other. Especially, HTCs vary with the wall subcooling to a negative exponent in Dehbi's correlation, while the exponent is positive in Liu's correlation. For the two