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Numerical analysis of steam condensation over a vertical surface in presence of air

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ABSTRACT

The passive containment cooling system (PCCS) is widely used in the advanced Generation III and III+ nuclear reactor systems to maintain the integrity of the containment under long term post utmost accidents like the loss of coolant accident (LOCA) and the main steam line break accident (MSLB). In the steam condensation process, the presence of large amounts of noncondensable gases (mainly air) will lead to the serious deterioration of heat transfer. Further research on steam condensation in the presence of air must be conducted. Condensation process of steam in the presence of air has been successfully modeled by applying a user defined function (UDF) added to the commercial computational fluid dynamics (CFD) package. Calculated profiles of temperature, air concentration, velocity components and condensation heat transfer coefficient (HTC) are compared to experimental results. The simulation results indicate that there is a good agreement between the experimental results and the model predictions. It also shows that both the latent and the sensible HTCs decreased with the increase of the air mass fraction, and the latent heat transfer is the dominant factor of the total condensation heat transfer when the air mass fraction less than 50%. Local latent HTC shows an upward tendency along the height direction of the heat transfer tube from bottom to top, with sensible HTC taking on an opposite trend.

1. Introduction

Part of new generation reactors are widely used passive containment cooling system (PCCS) in order to maintain the integrity of the containment under long term post utmost accidents like the loss of coolant accident (LOCA) and the main steam line break accident (MSLB). Based on double concrete containment, the condenser is one of the most essential equipment in the PCCS and its heat transfer capability determines the performance of the PCCS. In the steam condensation process, the presence of large amounts of noncondensable gases (mainly air) will lead to the serious deterioration of heat transfer (Ganguli et al., 2008; Rosa et al., 2009; Lee and Kim, 2008). The study of condensation of steam in the presence of air is necessary to be investigated.

For the current study of steam condensate in the presence of noncondensable gases, there are two categories, which are experimental and theoretical analyses. Though the empirical correlations that got from experimental studies have a highly practical value within their scopes, these correlations will serious deteriorate beyond their scopes (Uchida et al., 1965; Tagami, 1965; Dehbi, 1991; Liu et al., 2000). The classical methods and theories for the condensation heat transfer with broad applicability that get from experiments have not yet been formed by now. For engineering applications, to obtain or evaluate data by numerical simulation method is also one of economical and fast ways. Moreover, numerical simulation can even obtain the flow field characteristics and the dynamic characteristics of steam condensation process which is very hard for experiments to get.

The combined application of computational fluid dynamics (CFD) software and computer programming is the main way to achieve numerical simulation of steam condensation containing noncondensable gases. At present, the main numerical simulation method has two categories. One is to solve the heat and mass transfer processes in the condensation surface with the basic laws of physics (Andreani et al., 2001; Lycklama à Nijeholt and Hart, 2000; Smith et al., 2003). The numerical model is proposed under the principle of conservation of energy and mass by establishing a two-phase boundary in the presence of noncondensable gases. Another one is to use of heat and mass transfer developed integral equation (Martin-Valdepe~ nas et al., 2005; Rastogi, 2003; Siccama et al., 2003). These relationships are programmed as the source term of the governing equation which is applied to the cells near the condensing surface to achieve the numerical simulation of

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Nomenclature

General notation

A	area of near-wall grid cell (m^2)
C_p	specific heat capacity at constant pressure ($J\,kg^{-1}\,K^{-1}$)
C_i	adjustment factor ($W\,m^{-2}\,K^{-1}$)
D_0	mass diffusion coefficient under the standard state ($m^2\,s^{-1}$)
EXP	experiment
g	acceleration due to gravity ($m\,s^{-2}$)
h	heat transfer coefficient ($W\,m^{-2}\,K^{-1}$)
h_0	Heat transfer coefficient obtained from experiments ($W\,m^{-2}\,K^{-1}$)
h_{lg}	latent heat of vaporization of saturated steam ($J\,kg^{-1}$)
H_0	heat (J)
L	axial distance (m)
m	condensate rate ($kg\,s^{-1}$)
M	molar mass ($kg\,mol^{-1}$)
N	volume fraction
P	pressure (Pa)
P_0	pressure under standard conditions (101325 Pa)
P_{sp}	steam partial pressure (Pa)
r	radial distance (m)
R	molar gas constant (8.3145 $J\,mol^{-1}\,K^{-1}$)
SIM	simulation
T	temperature (K)
T_0	temperature under standard conditions (273.15 K)
T_{ref}	temperature with the enthalpy value of 0 (273.15 K)
u	velocity of flow ($m\,s^{-1}$)
W	mass fraction
X	relative molecular mass

Greek symbols

α	the index of temperature ratio
δ	film thickness (m)
ρ	cooling water density ($kg\,m^{-3}$)

Subscripts

a	air
b	bulk
cond	condensation heat transfer
conv	convective heat transfer
f	film
g	gas
mix	gases mixture
s	steam
w	wall

the condensation process. Since the first method requires a lot of programming and quite detailed cells, it cannot be widely applicable for the engineering applications. However, the second method can rapidly simulate the changes in the process of condensation heat transfer and the flow field, which has a high value for the engineering.

In the present work, the CFD code conducted by the second method is used to simulate experiments that performed in the TOSQAN (Cornet et al., 2002) and the Su et al. (2013) facility. The simulation is performed with the knowledge of experimental results. Ten steady states are simulated in the present work. The main purpose is to reproduce the atmosphere during steady state conditions, given that the steam condensation coefficient is calculated adequately. Calculated profiles of condensation coefficient, temperature, and air mass fraction are compared to the experimental results.

2. Input model

2.1. Condensing models and theoretical assumptions

Air molecules will move to the condensation interface along with condensing of the steam molecules, and accumulated on the interface of the gas–liquid producing a noncondensable gas boundary. The steam molecules that condensing on the gas–liquid surface need to pass through the noncondensable gas boundary. This process increases the mass transfer resistance, hindered the rate of steam condensation. Since the air accumulated on the liquid film surface, the partial pressure of air at here will be higher than the gases bulk. Thereby, a driving force that conduct air molecules to diffuse from the interface to the gases bulk is generated. On the contrary, the partial pressure of steam in the gases bulk is higher than that on the liquid film surface, which will make the steam molecules diffuse to the liquid film surface. The diffusion of steam and air molecules maintain a dynamic equilibrium process to make the total pressure constant. The two-dimensional physical model of steam condensation containing air on a vertical wall surface is shown in Fig. 1.

The steam condensation heat transfer process is usually considered to the steam condensation heat transfer between the gases bulk and the condensing wall. Colburn (1934) divided the heat of

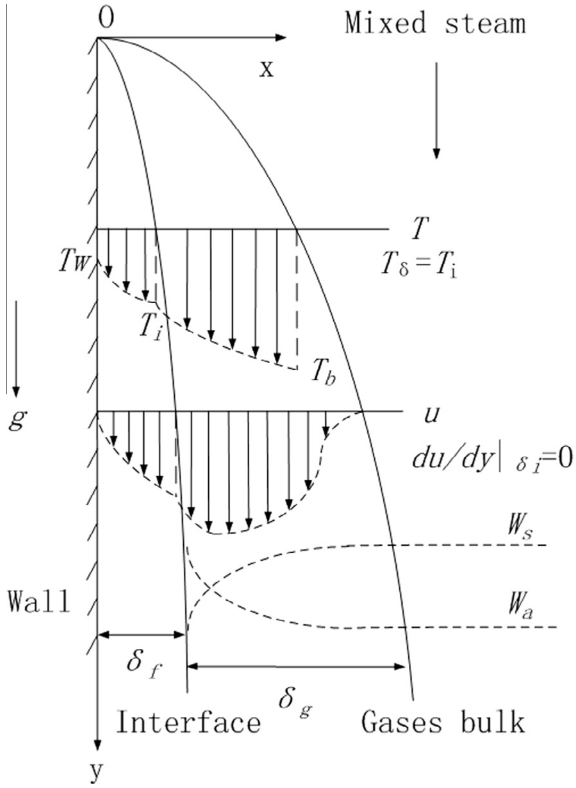

Fig. 1. Coordinate system and related physical.