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Scaling analysis of coolant spraying process in automatic depressurized system

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ABSTRACT

Through the automatic depressurized system of AP1000 reactor, the steam with high temperature and high pressure from the pressurizer sprays into the water tank, and the pressure in the primary coolant system will diminish to protect the reactor. However, as the steam continues to flow into the tank, the water temperature rises rapidly until boiling occurs, which will affect the local heat transfer process. Therefore, it is necessary to understand the corresponding heat transfer mechanism by means of experiment. To ensure that the experimental results with a scale-down model reflect the actual situations of the prototype we analyzed the process of steam jetting from the pipeline into the water tank, and summarized scaling rules based on equation analysis method, including various flow stages. The results show that the phenomena-based similarity between the model and the prototype should meet: (1) geometrically similar model and prototype; (2) equal thermal parameters and identical initial conditions, which can greatly simplify other similarity parameters; (3) at the blowdown stage, keep the steam mass flux and the nozzle diameter consistent; (4) at the natural convection stage with single phase fluid, the equality in terms of Prandtl number and the Grashof number should be met first, while assessing the relative uncertainty.

1. Introduction

In recent years, the passive technology becomes a very popular technology in many industrial fields, especially in the Ap1000 reactors, the third generation reactors. For example, in AP1000 PXS (Passive Core Cooling System), the steam with high temperature and high pressure sprays into the built-in refueling water storage tank (IRWST) through ADS (Automatic Depressurized System) to condensate as it discharges from the pressurizer, which can provide overpressure protection for the primary coolant system. However, under some accident conditions, the steam continues to flow into the IRWST through ADS pipeline, this causes the water temperature rising rapidly until boiling, this also affects the local heat transfer processes and IRWST draining behaviors. Therefore, it is necessary to study the pool boiling phenomenon in IRWST under the condition of steam blowdown state, especially to understand the heat transfer mechanism thoroughly, which is of great significance to the reactor safety.

As the complexity of heat transfer mechanism, people have carried out many experimental investigation and theoretical simulation to study the steam-direct-jetting condensation and boiling phenomenon, which is an important step toward the ADS discharging processes. Chun et al. (1996) designed the VAPORE experimental facility to perform thermomechanical and fluid-dynamic tests on relative nuclear components and systems, including the ADS test. It has a full-scaled and full-pressurized configuration of the AP600 ADS system. Two phases were carried out in their experiments: phase A were implemented for the ADS-1/2/3 with steam flow through a sparger into IRWST to evaluate the capacity of the sparger, and phase B focuses on the thermal hydraulic behavior on ADS valves, pipes and sparger. Based on a reduced-height and reduced-pressure integral loop test facility, Song et al. (2007) investigated the direct contact condensation of steam in a water pool and developed a condensation regime map of the steam jet for simplified spargers.

In addition, many researchers focused on the fundamental mechanism study of direct contact condensation in a simplified water tank. Based on visual techniques, they observed conical, ellipsoidal and divergent shapes of steam plume, although which these shapes depends on the test conditions Giovanni

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Nomenclature

a	interfacial area per unit volume, m^{-1}
p	pressure, N/m^2
α	volume fraction
ρ	density of fluid, kg/m^3
g	acceleration of gravity, m/s^2
A	area, m^2
De	hydraulic diameter, m
e	total specific energy, J/kg
H_{gs}	the saturation enthalpy of the gas phase, J/kg
H_{fs}	the saturation enthalpy of the liquid phase, J/kg
Hf	the average specific enthalpy, J/kg
f	friction coefficient
t	time, s
q_f	heat flux from the liquid phase into the interface, w/m^2
q_g	heat flux from the gas phase into the interface, w/m^2
q_s	heat flux, w/m^2
q_v	internal heat source per unit volume, w/m^3
d_b	bubble diameter, m
H	the height of the water surface in the tank, m
C_D	drag coefficient
L	characteristics length, m
L_0	submerged depth from sparger to water level, m
P_0	pressure at the free surface of water tank, N/m^2
Γ	generate rate of liquid phase, $kg/(m^3\ s)$
$\dot{m}_{gf}$	mass flux from gas phase into liquid phase, $kg/(m^2\ s)$
V	velocity, m/s
$V_{g,ex}$	steam velocity at the nozzle exit, m/s
k	drag coefficient
r	radial direction, m
z	axial direction, m
h	coefficient of convection heat transfer, $w/(m^2\ k)$
h_f	heat transfer coefficient of the liquid phase across the interface, $w/(m^2\ k)$
h_g	heat transfer coefficient of the gas phase across the interface, $w/(m^2\ k)$
Q_{gf}	heat exchange across the interface per unit volume, w/m^3
K_f	thermal conductivity of the liquid phase, w/(m k)
Nu_f	Nusselt number of the liquid phase
Re	Reynolds number of the liquid phase
Pr	Prandtl number of the liquid phase
μ_f	viscosity of liquid phase, Pa s
D	diameter of the orifice, m
B	dimensionless subcooling of the liquid
G_0	mass flux of the steam, $kg/(m^2\ s)$
G_m	reference mass flux of the steam, $kg/(m^2\ s)$
Gr	Grashof number
Pr	Prandtl number
T_∞	bath temperature, K
Ts	temperature of the interface between the gas phase and the liquid phase
C_p	specific heat of the liquid, J/(kg K)
h_fg	latent of heat, J/kg
k_{gf}	interface momentum force per unit volume, N/m^3
s	velocity ratio of the gas phase and the liquid one

Subscript

f	liquid
g	gas
r	value at the radial direction
z	value at the axial direction
0	initial value (or reference value)
ex	value at the orifice exit

et al. (1984), Chun et al. (1996), Kim et al. (2001). Using different horizontal (or vertical) nozzles under various conditions of pool water temperature and steam mass flux, Kerney et al. (1972) and Weimer et al. (1973) studied the penetration length of sonic steam jet with experimental and theoretical approaches, they obtained the classical correlations to calculate the dimensionless penetration length. Chun et al. (1996), Kim et al. (2001), Wu et al. (2009) and Tobias et al. (2011) derived and modified the similar empirical correlations for the plume length, and With (2009) introduced a new two-dimensional steam plume length diagram to predict length accurately for a wide range of conditions. Furthermore, many researchers have provided semi-empirical correlations to evaluate the average heat transfer coefficient around the steam plume interface Simpson and Chan (1982), Chun et al. (1996), Seong et al. (2000), Kim et al. (2001), Kim et al. (2004), Wu et al. (2007), Park et al. (2007). Ajmal et al. (2010) studied the phenomenon of direct-contact condensation numerically by introducing a thermal equilibrium model, and revealed the relationship between dimensionless penetration length of steam plume and the condensation heat transfer coefficient. Other related studies also depicted the structures of the corresponding flowing field, including the instantaneous velocity field, void variation and temperature distribution Van Wissen et al. (2004), Takase et al. (2002), Dahikar et al. (2010).

However, all of these experimental researches had greatly simplified the relative test section. Therefore, these experimental conclusions cannot be directly used for the condensing and pool boiling induced by the steam blowdown under the reactor accident. In general, limited by the test size, the experiments can only be implemented with a scale-down model. Therefore, it is necessary to carry out corresponding scaling analysis to validate whether the results from the experimental model can reflect the real prototype phenomenon accurately. Based on the mass and energy balances and the flow-pressure drop relationship, Hsu et al. (1990) conducted a scaling study on the test equipment at the case of small break LOCA, and concluded that the coolant capacity is a more important similarity parameter. Sonin (1981) studied the scaling-down problem on the steam jetting stage in the boiling water reactor with dimensional analysis method, obtaining some general similarity criterion, and revealing that the steam mass flux and the relative thermodynamic properties are the key factors for scaling similarity. Zuber et al. (1998) developed an integrated scaling methodology: hierarchical two-tiered scaling (H2TS), in which the relative scaling analysis on a complex system is divided into four steps: system decomposition, scale identification, system scaling analysis and process scaling analysis, and a crucial problem is to obtain the corresponding similarity criteria based on the field equations. This method has been widely used for its effectiveness on larger system research.

In this study, combining with the above H2TS solution, we use a scaling method based on equation analysis to further study the similarity problem at each stage in which the steam with high temperature and high pressure injected into the cold water pool, and also summarize the relative scaling ratios for design reference.

2. Objective and process description

As shown in Fig. 1, the steam with high temperature and high pressure flows into the connecting pipes as the ADS is activated, and jets into the IRWST through a sparger. At the third stage, the