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Simulation of Two-Phase Natural Circulation Loop for Core Cather Cooling Using Air Water

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1. Introduction

A closed loop natural circulation system employs thermally induced density gradients in single phase or two-phase liquid form to induce circulation of the working fluid thereby obviating the need for any mechanical moving parts such as pumps and pump controls. This increases the reliability and safety of the cooling system and reduces installation, operation and maintenance costs. That is the reason natural circulation cooling has been considered in advanced reactor core cooling and in engineered safety systems. Natural circulation cooling has been proposed to remove reactor decay heat by external vessel cooling for in-vessel core retention during sever accident scenario [1,2]. Recently in APR1400 reactor core catcher design natural circulation cooling is proposed to stabilize and cool the corium ejected from the reactor vessel following core melt and breach of reactor vessel [3]. The natural circulation flow is similar to external vessel cooling where water flows through an inclined narrow gap below hot surface and is heated to produce boiling. The two-phase natural circulation enables cooling of the corium pool collected on core catcher. Due to importance of this problem this paper focuses simulation of the two-phase natural circulation through inclined gap using air-water system. Scaling criteria for air-water loop are derived that enable simulation of the flow regimes and natural circulation flow rates in such systems using air-water system.

2. Scaling of Two-Phase Natural Circulation

In the prototype core catcher cooling system the two-phase natural circulation is driven by steam-water where boiling process at inclined region creates sufficient bubbles to establish stable flow. For a two-phase natural circulation system, similarity groups have been developed from a perturbation analysis based on the one-dimensional drift flux model. The set of mass, momentum and energy equations are integrated along the loop, and the transfer functions between the inlet perturbation and various variables are obtained. The four equation drift flux model consisting of the mixture mass, momentum and energy equations and vapor continuity equation is analytically integrated along the flow path. From this, the integral response functions between various variables such as the velocity, density, void fraction, enthalpy and pressure drop are obtained. The non-dimensionalization of these response functions yields the key integral scaling parameters. From these, the scaling criteria for dynamic simulation can be obtained [4]. The important dimensionless groups that characterize the kinematic, dynamic and energy similarities are for two-phase are given in Table 1.

Table 1. Two-Phase Similarity Parameters

Phase Change No.	$N_{pch}\equiv\left(\frac{4q_o'''\delta l_o}{du_o\rho_{f}7i_{fg}}\right)\left(\frac{\Delta\rho}{\rho_g}\right)=N_{Zu}$
Subcooling No.	$N_{sub}\equiv\left(\frac{i_{sub}}{i_{fg}}\right)\left(\frac{\Delta\rho}{\rho_g}\right)$
Froud No.	$N_{Fr}\equiv\left(\frac{u_o^2}{gl_o\alpha_o}\right)\left(\frac{\rho_f}{\Delta\rho}\right)$
Drift-flux No.	$N_{di}\equiv\left(\frac{V_{gj}}{u_o}\right)_i$ (Void-Quality Relation)
Time Ratio No.	$T_i^*\equiv\left(\frac{l_o/u_o}{\delta^2/\alpha_s}\right)_i$
Thermal Inertia Ratio,	$N_{thi}\equiv\left(\frac{\rho_s c_{ps}\delta}{\rho_f c_{pf} d}\right)_i$
Friction No.	$N_{fi}\equiv\left(\frac{fl}{d}\right)_i\left[\frac{1+x(\Delta\rho/\rho_g)}{(1+x\Delta\mu/\mu_g)^{0.25}}\right]\left(\frac{a_o}{a_i}\right)^2$
Orifice No.	$N_{oi}\equiv K_i\left[1+x^{3/2}(\Delta\rho/\rho_g)\right]\left(\frac{a_o}{a_i}\right)^2$
where	$\alpha_o=\left(\frac{\rho_f}{\Delta\rho}\right)\left(\frac{1}{1+(N_d+1)/(N_{Zu}-N_{sub})}\right)$.

The scaling of the natural circulation with air air-water system requires fluid-fluid scaling consideration for flow dynamic similarity. The void fraction is related to quality through void quality relation. The drift velocity between gas liquid phase The x_e the vapor quality at the exit of the heated section in prototype from the similarity of the Zuber and subcooling numbers yields: $(x_e)_R\left(\frac{\Delta\rho}{\rho_g}\right)_R=1$ .This indicates that the vapor quality should be scaled by the density ratio. If this condition is satisfied, the friction similarity in terms of N_{fi} and N_{oi} can be approximated by dropping the terms related to the two-phase friction multiplier.

Furthermore, by definition it can be shown that $N_d = \left(\frac{\Delta\rho}{\rho_g} x_e\right)\left(\frac{\rho_f}{\Delta\rho\alpha_o} - 1\right) - 1$ Therefore, similarity of the drift flux number requires void fraction similarity. $(\alpha_e)_R \left(\frac{\Delta\rho}{\rho_f}\right)_R = 1 \, or \, (\alpha_e)_R \approx 1$. Also, since V_{gj} depends on the flow regime, this group parameter also characterizes the flow pattern. The density ratio group, given by the $(\Delta\rho/\rho_g)$ term, scales the fluids. This also appears in the groups N_{sub}, N_{pch}, N_f, and N_o. The representative constitutive equation for the relative motion based on the drift velocity correlation is given by: $V_{gj} = 0.2\left(1 - \sqrt{\frac{\rho_g}{\rho_f}}\right) j + 1.4\left(\frac{\sigma g \Delta\rho}{\rho_f^2}\right)^{\frac{1}{4}}$. where the volumetric flux, j, in the heated section is given by: $j = \left(1 + x\left(\frac{\Delta\rho}{\rho_g}\right)\right) u_o$.

The classical void-quality correlation is: $\alpha = \alpha\left(x, \left(\frac{\rho_g}{\rho_f}\right), \left(\frac{\mu_g}{\mu_f}\right), etc.\right)$. The relative motion similarity based on the drift velocity correlation becomes, $N_d = 0.2\left(1 - \sqrt{\frac{\rho_g}{\rho_f}}\right)\left[1 + x\left(\frac{\Delta\rho}{\rho_g}\right)\right] + \frac{1.4}{u_o}\left(\frac{\sigma g \Delta\rho}{\rho_f^2}\right)^{\frac{1}{4}}$.

3. Air-Water Simulation

Simulation of steam-water natural circulation is carried out with air-water flow in an inclined rectangular channel with set of geometrical parameters corresponding to a core catcher design by Song et al. [4]. A schematic of the test geometry is shown in Figure 1, where the steam generated is replaced by air injection rate. The heat flux corresponding to the decay heat is simulated with air flux to the test section to produce equivalent flow quality.

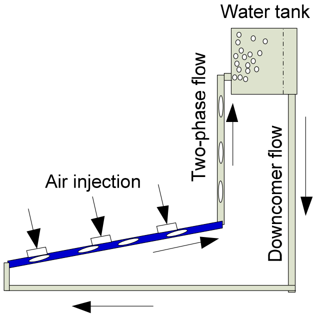

Figure 1. Schematic of air-water simulation loop

Design calculations were carried out for typical core catcher design to estimate the expected natural circulation rates. In Figure 2 and 3 the natural circulation flow rate of the water and two-phase pressure drop are shown for different air injection rate expressed as void fraction for a select downcomer pipe size. These results can be scaled to steam water system using scaling consideration presented in section 2.

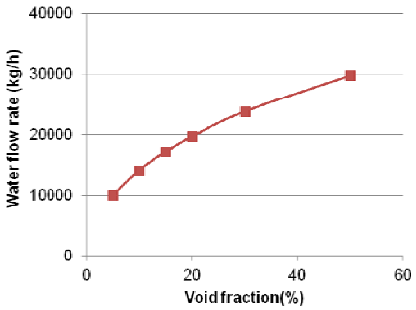

Fig. 2. Natural circulation flow rate

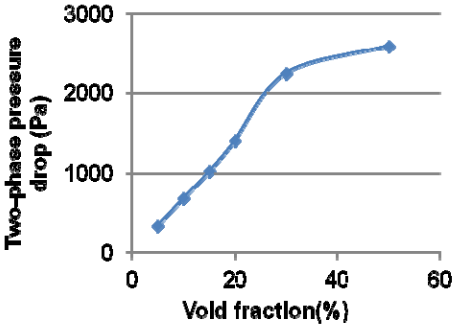

Fig. 3. Two-phase pressure drop

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