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Study on a Scaling Method and Design of an Air-Water Flow Test Facility

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1. Introduction

In this research, the objectives are to design a test facility for analyzing the behaviors of an air-water two-fluid flow. To mitigate a distortion of flow behaviors, scaling laws and local phenomena were analyzed. Based on a three-level scaling method, scaling analysis was conducted. These results demonstrate that the design of air-water flow test facility will be able to predict the air-water flow behaviors.

2. Scaling law

2.1 General review

There are some scaling laws to design the test facility, including linear scaling, volume scaling, and three-level scaling. Most of the scaling methods are derived by governing equations to satisfy global similarity. In a linear scaling method, aspect ratio (l/d) and velocity scales are conserved between the original system and test facility [5]. However, it has reduced time scale and increased acceleration scale (gravitational force). In a volume scaling method, height and main flow length of the original system are conserved with a modified flow area. The flow velocity and acceleration were conserved. However, owing to a fixed height and flow length, it is necessary to have a lot of space. Moreover, the excessive influence of wall friction is presented owing to the large aspect ratio(l/d) in case of a small test facility volume. Therefore, these methods are not appropriate for two-phase flow and pipe break test, which have a large gravity influence and fast-changing phenomena.

Ishii and Kataoka presented a three-level scaling method that can be applied to a two-phase natural/forced circulation test [6, 7]. It consists of 1) global scaling, 2) boundary flow & inventory scaling, and 3) local scaling. The first level of scaling is focused on mass, momentum, and energy conservation. And then, boundary flow and inventory scaling are considered in the second level of scaling. In the final level of scaling, local phenomena of each component and its effect of the global scaling are deeply analyzed. Therefore, the three-level scaling method is used to mitigate flow distortion phenomena of the test facility. Table. I shows the summary of scaling parameters in previous researches.

Table I: The summary of scaling parameters in previous researches [1-3]

Parameter	Symbol	Parameter ratio (model/prototype)		
		Volume scaling	Linear scaling	Three-level scaling
Length	l_R	1	l_R	l_R
Diameter	d_R	d_R	l_R	d_R
Area	a_R	d_R^2	l_R^2	d_R^2
Volume	V_R	d_R^2	l_R^3	$a_R l_R$
Core dT	ΔT_R	1	-	1
Velocity	u_R	1	1	$l_R^{1/2}$
Time	t_R	1	l_R	$l_R^{1/2}$
Gravity	g_R	1	$1/l_R$	1
Power/volume	q_R'''	1	$1/l_R$	$1/l_R$
Heat flux	q_R''	1	$1/l_R$	$1/l_R$
Core power	q_R	d_R^2	l_R^2	a_R
Rod diameter	rd_R	1	1	1
Number of rods	n_R	d_R^2	l_R^2	a_R
Flow rate	$\dot{m}_R$	d_R^2	l_R^2	$a_R l_R^{1/2}$
di subcooling	Δi_{sR}	1	1	1
dT subcooling	ΔT_{sR}	1	1	1

2.2 Application

Level. 1 Global scaling

Based on the three-level scaling method, the test facility is currently being designed. In first level of scaling, mass and momentum conservations are used to design the test facility. Table. II shows dimensionless numbers based on conservation equations.

Continuity equation

$$\frac{\partial \rho_m}{\partial t} + \frac{\partial}{\partial z}(\rho_m u_m) = 0 \tag{1}$$

$$\frac{\partial \alpha \rho_g}{\partial t} + \frac{\partial}{\partial z}(\alpha \rho_g u_m) = G_{air,p} - \frac{\partial}{\partial z}(\frac{\alpha \rho_g \rho}{\rho_m} V_{gj}) \tag{2}$$

Momentum equation

$$\frac{\partial \rho_m u_m}{\partial t} + \frac{\partial}{\partial z}(\rho_m u_m^2) = -\frac{\partial p_m}{\partial z} - \rho_m g - \frac{\partial}{\partial z}\left(\frac{\alpha \rho_g \rho}{(1-\alpha)\rho_m} V_{gj}^2\right) - (\frac{f_m}{2D} + \frac{K}{2}\delta(z - z_i))\rho_m u_m |u_m| \tag{3}$$

Table. II: Dimensionless numbers based on global scaling

Dimensionless number	Equation	Ratio
Air source number	$N_{AS} = \frac{G_{aso}}{\rho_{g0}}\frac{l_0}{u_{g0}}$	1.00
Drift number	$N_{dri} = \frac{\rho_{f0}}{\rho_{m0}}\frac{V_{gj0}}{u_{g0}}$	1.01
Froude number	$N_{froude} = \sqrt{\frac{u_{m0}^2}{g_z l_0}}$	0.96
Density ratio	$R_d = \frac{\rho}{\rho_g}$	1.00
Friction number	$N_{fr} = \frac{f_m}{2D^*}$	1.00

Level. 2 Boundary flow & inventory scaling

In second level of scaling, the boundary flow is determined by the flow and pressure of reference data.

Level. 3 Local phenomena scaling

The tank has a slow flow velocity due to large cross-sectional area, therefore, it can be a role of separator between air and water. Therefore, it is important to mitigate the distortion including air stratification, flow regime, and bubble break-up. Based on local phenomena inside the tank, dimensionless numbers are determined, as listed in Table. III.

Table. III: Dimensionless numbers in tank

Dimensionless number	Equation	Ratio
Reynolds number (bubble)	$N_{Re} = \frac{\rho V_{fg} D_b}{\mu_l}$	1.00
Weber number	$N_{we} = \frac{\rho u^2 l}{\sigma}$	0.99
Bond number	$N_{Eo} = \frac{g D_b^2 \Delta\rho}{\sigma}$	1.00
Froude number (level)	$N_{froude} = \sqrt{\frac{u_{m0}^2}{g_z h_{level}}}$	1.00~1.36
Froude number (outlet pipe)	$N_{froude} = \sqrt{\frac{u_{m0}^2}{g_z D_{outlet}}}$	1.19
Drag coefficient	$C_D = \frac{4}{3}\frac{D_b g}{V_{fg}^2}\frac{\Delta\rho}{\rho_l}$	1.00

3. Test facility

Figure 1 shows the conceptual design of the test facility. To present the effect of test condition, a test matrix of experiments is listed in Table IV.

Table IV: Test matrix of the experiments

Test parameters	Values	Unit
Pressure difference	10.0-50.0	kPa
Size	1.0-6.0	inch
Aspect ratio	1-36	-
Geometry	circle, ellipse	-

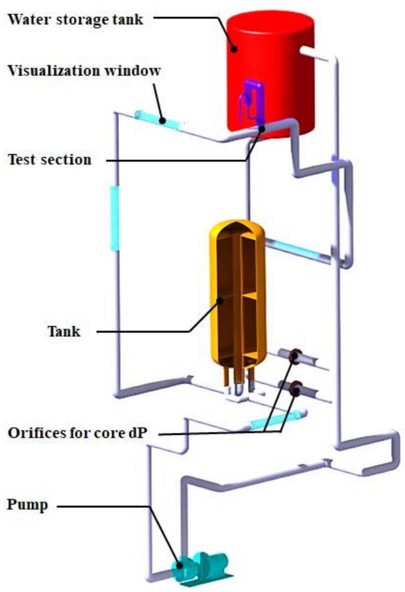

Fig. 1 Conceptual design of the test facility

4. Conclusions and further works

The experimental test was proposed to present the air entrainment and air-water two-fluid flow behaviors. Scaling analysis was conducted to design the test facility for transient condition. Three-level scaling method was considered and calculated to mitigate the flow distortion in the test facility.

The scaling of the main components such as the break region and the tank was currently being analyzed. After scaling law of the test facility is satisfied, the experimental test will be conducted.

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