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Scaling Analysis of the Single-Phase Natural Circulation: the Hydraulic Similarity

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ABSTRACT

More and more advanced or newly designed nuclear reactors adopt passive safety systems which rely only on natural forces to operate. During the operation of such systems, only natural circulation flow is present as no external force induced by pumps is exerted on them. The performance of such systems is generally simulated with a scaled-down model. To simulate similar hydraulic behaviors of these systems with a reduced-scale model, a tractable and accurate scaling methodology should be developed. For reduced-scale model, there is still debate on whether full-height or reduced-height scaling can better preserve the natural circulation flow.

In this study, a dimensionless integral loop momentum equation is derived to produce the hydraulic similarity groups. From the dimensionless equation, two dimensionless numbers, the dimensionless flow resistance number and the dimensionless gravitational force number, are identified along with a unique hydraulic time scale, characterizing the system hydraulic response. The identified dimensionless numbers are the applied to derive a set of scaling criteria for the design of a full-pressure reduced-size similar model for a PWR (Pressurized Water Reactor). For exact hydraulic similarity, it is found that the scaling ratio of the pipe inner diameter should be related to that of the pipe length. In addition, the relative length scaling ratio and the relative cross-sectional scaling ratio should also be preserved between the model and the prototype in order to have similar hydraulic behavior. To assess the proposed scaling methodology, a simple rectangular prototype loop, its corresponding model developed on the basis of the proposed scaling criteria and a full-height model are developed. The simulation results of the prototype and the proposed two models for total loss of flow accident show that the proposed scaling methodology can well preserve the hydraulic behavior of a single-phase natural circulation system.

I. INTRODUCTION

In the newly designed nuclear reactors, the passive safety systems are generally adopted to enhance the safety of nuclear systems, such as the passive core cooling system (PXS) in the AP1000 [1] and the Passive Auxiliary Feedwater System (PAFS) in the APR+ [2]. As these passive safety systems are newly proposed and was never put into practice use, their reliability and performances are under question. Thus, the reliability and performance of these systems must be assessed by extensive thermal-hydraulic tests. As the size and power of a nuclear system is large, these tests are usually performed in a reduced-size test facility due to the economic and safety concern, e.g. the APEX-1000 [3], a 1/4-height 1/2-time-scale reduced pressure integral systems facility, for the AP1000, and the ATLAS-PAFS [4] for the APR1400. These passive safety systems all rely on the natural circulation to cool down the reactor cores during an accident. Thus, a robust and accurate scaling methodology must be developed and employed to both assist in the design of a scaled-down test facility and guide the tests in order to mimic the natural circulation flow of its prototype. The natural circulation system generally consists of a heat source, the connecting pipes and several heat sinks.

Although many applauding scaling methodologies have been proposed during last several decades, few works have been dedicated to systematically analyze and exactly preserve the hydraulic similarity. In the present study, the hydraulic similarity analyses are performed at both system and local level. By this mean, the scaling criteria for the exact hydraulic similarity in a full-pressure model have been sought. In other words, not only the system-level but also the local-level hydraulic similarities are pursued. As the hydraulic characteristics of a fluid system is governed by the momentum equation, the scaling analysis starts with it. A dimensionless integral loop momentum equation is derived to obtain the dimensionless numbers. In the dimensionless momentum equation, two dimensionless numbers, the dimensionless flow resistance number and the dimensionless gravitational force number, are identified along with a unique hydraulic time scale, characterizing the system hydraulic response. These dimensionless numbers are then applied to obtain a set of scaling criteria for the design of a full-pressure model for a PWR to preserve the similar hydraulic behavior of single-phase natural circulation. The scaling criteria obtained for a full-pressure model are then used to produce a scaled-down model with respect to a simple rectangular prototype loop proposed. In addition, a full-height full-pressure model is also made to see which model among the full-height model and reduced-height model can preserve the hydraulic behavior of the prototype.

II. DERIVATION OF THE HYDRAULIC SIMILARITY GROUPS

The dimensionless integral loop momentum equation can be written as

$$\frac{1}{\dot{m}_0}\frac{\partial \dot{m}}{\partial t}\sum_{i}^{N}\frac{l_i}{u_0}\frac{a_0}{a_i}=-\frac{\dot{m}^2}{\dot{m}_0^2}\sum_{i}^{N}\left(f\frac{l}{d}+K\right)_i\frac{a_0^2}{2a_i^2}+\frac{\left(\rho_C-\rho_H\right)g\,\Delta h_{th}}{\rho_0 u_0^2} \tag{1}$$

Where $\dot{m}_0$ is the initial loop flow rate; i represents any component section in a loop such as the reactor core, the hot leg, the SG U-tubes, l_i is the length of ith section; a_i is the cross-sectional area of ith section; $\left(f\frac{l}{d}+K\right)_i$ is the sum of the frictional and the form loss of ith section; ρ_C and ρ_H are the average densities of fluids in the colder section and the hotter section, respectively; and Δh_{th} is the elevation difference between thermal centers of heat sink and heat source.

Hydraulic time scale:

$$\tau=\sum_{i}^{N}\frac{l_i}{u_0}\frac{a_0}{a_i} \tag{2}$$

Dimensionless flow resistance number:

$$N_r=\sum_{i}^{N}\left(f\frac{l}{d}+K\right)_i\frac{a_0^2}{2a_i^2} \tag{3}$$

Dimensionless gravitational force number:

$$N_g=\frac{\left(\rho_C-\rho_H\right)g\,\Delta h_{th}}{\rho_0 u_0^2} \tag{4}$$

The hydraulic time scale is the time period that characterizes the fluid hydraulic transport time of a loop. For example, the shorter the loop length is, the faster a fluid element can run through a loop for a given velocity; analogically, the higher the fluid velocity is, the faster a fluid element can run through a loop. The dimensionless flow resistance number says something about the flow resistance characteristics of a loop: the higher the N_r is, more rapidly the flow decreases. The dimensionless gravitational force number is related to the gravitational force of a loop. If the last two dimensionless parameters (or term them as similarity parameters) are made equal between a scaled-down test facility and its prototype, the hydraulic similarity of both systems will be exactly preserved. In the next section, it will be illustrated that how these similarity parameters will be utilized to assist in designing a full-pressure scaled-down test facility with similar hydraulic characteristics for a PWR (Pressurized Water Reactor).

III. APPLICATION TO A FULL-PRESSURE SCALING FOR THE PWRS

Before proceeding to the application of the proposed scaling methodology, let's first define the dimensionless number ratio of a model to a prototype.

$$N_{xR}=\frac{\left[N_x\right]_m}{\left[N_x\right]_p} \tag{5}$$

Where N_x stands for the dimensionless number for the x physical process or phenomena; $\left[N_x\right]_m$ and $\left[N_x\right]_p$ the dimensionless number in the model and in the prototype, respectively; N_{xR} the ratio of both dimensionless numbers.

Only when $N_{xR}=1$, the exact similarity of the x physical process or phenomena is achieved between a model and its prototype. For the hydraulic transport processes during the single phase natural circulation in a PWR, only the gravitational force and the flow resistance force are present. As long as they are preserved between the model and the prototype, exact hydraulic similarity might be expected.

By applying the above similarity law to the derived dimensionless numbers for the pipe and the SG, a set of scaling criteria for the design of a full-pressure reduced-size model for a PWR can be obtained, as summarized in **Table 1**.

Table 1. Scaling criteria for the full-pressure scaling

Full-Pressure Exact Scaling	Scaling Criteria	# of Tubes
Area Scaling	$\left[\frac{a_i}{a_0}\right]_R=1.$	-
Pipe	$d_R=l_R^{3/4}.$	-
SG	$d_R=l_R^{0.75}.$	$N_R=1.$
Mass Flow Rate	$\dot{m}_R=l_R^2$	-

IV. DEMONSTRATION OF THE HYDRAULIC SIMILARITY IN A SIMPLE LOOP

In order to show the accuracy and applicability of the proposed scaling methodology, a simple prototype loop is proposed, as shown in **Fig. 1 (a)**. Based on this simple loop, a model with full height scaling is developed, and is named as Model 2 for convenience, as shown in **Fig. 1 (b)**. In addition, a model with 1/4-length scale with respective to the prototype is developed using the proposed scaling methodology, as shown in **Fig. 1 (c)**. The scaling ratios for important parameters are summarized in **Table 2**.

Table 2. Scaling ratios for the full-height and the reduced-height models

Parameters	Scaling Criteria	Scaling Ratio	
		Model 1 (Full Height)	**Model 2** (Current Scaling)
Length	$\left[\dfrac{l_i}{l_0}\right]_R$	1	1/4
Pipe Diameter	$d_R = l_R^{3/4}$	35.4%	35.4%
Length/Diameter	l_R / d_R	2.825	0.707
Mass Flow Rate	$\dot{m}_R = l_R^2$	1.25%	6.25%
Time scale	$\tau_R = \left(\sum_i^N \dfrac{l_i}{u_0}\right)_R$	1	1/2

The prototypical simple loop and both models proposed are simulated with the MARS-KS code [5]. The MARS-KS code is a system analysis code developed by KAERI by combining the RELAP5/MOD3.3 code and the COBRA-TF code [6]. The prototypical loop and two models run at the same pressure of 15 MPa and temperature of 267.0 ^{o}C. In the simple prototypical loop, the coolant is circulated at 10 kg/s. At the time of 0 s, the forced flow is interrupted, and the natural circulation is established. In the model 1 with full height, the coolant initially flows at 0.125 kg/s according to the flow rate scaling ratio, and is also changed to the natural circulation at the time of 0 s; in the model 2 with reduced height, the coolant initially is forced to flow at 0.625 kg/s at 15 MPa, and is changed to the natural circulation at the time of 0 s.

The mass flows in the loop from both models are compared with that from the prototype. In **Fig. 2**, the transient of the loop mass flow rate from the model 1 (full height) is compared with that from the prototype. As shown, the loop mass flow rate in the full-height model decreases faster than that from the prototype. It is because, for the full-height scaling, the frictional resistance is much larger than the desired one.

The transient of the loop mass flow rate from the model 2 (reduced height) is compared with that from the prototype in **Fig. 3**. As seen, the loop flow rate transient from the model 2 coincides with that from the prototype at the similarity scale. It means that the hydraulic similarity is exactly preserved in the model 2 with the proposed scaling methodology. From these comparisons, it is found that the full height scaling cannot preserve the hydraulic frictional similarity, but the reduced-height scaling is able to.

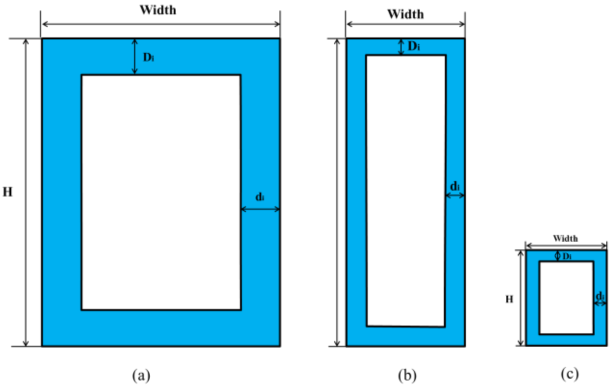

Fig. 1 The schematics of (a) the prototype, (b) the model 1 (full height) and (c) the model 2 (1/4-length scale)

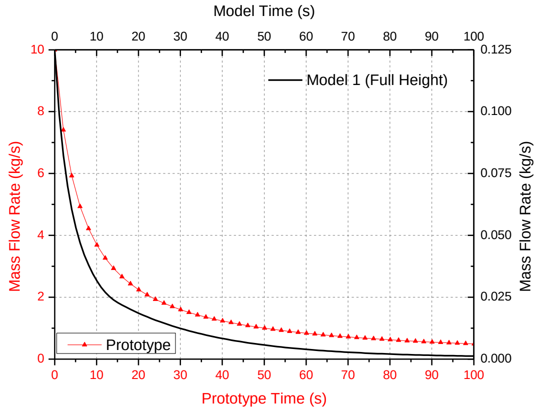

Fig. 2 Loop mass flow rates of the prototype and the model (full height)

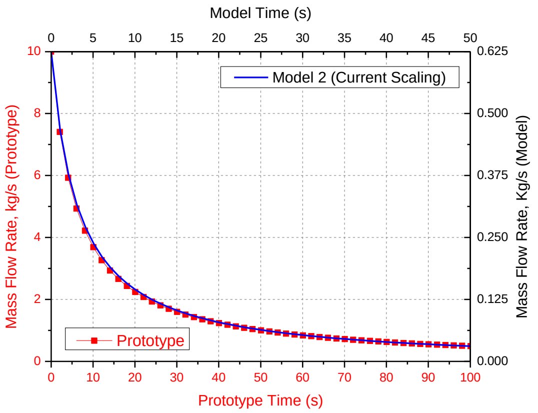

Fig. 3 Loop mass flow rates of the prototype and the model (current scaling)

V. CONCLUSION

From the dimensionless integral momentum equation, a unique hydraulic time scale, which characterizes the hydraulic response of a single-phase natural circulation system, is identified along with two dimensionless parameters: the dimensionless flow resistance number and the dimensionless gravitational force number. By satisfying the equality of both dimensionless numbers between the model and the prototype, a set of scaling criteria for exact hydraulic similarity are developed. Particularly, it is found that the scaling of the pipe inner diameter should be scaled down in relation to that of the pipe length, if the exact hydraulic similarity is preserved for a pipe. In addition, the relative pipe length ratio and the cross-sectional area ratio should be kept same between the model and the prototype.

Based on the developed scaling criteria, a full-pressure reduced-height model is developed with respect a simple prototype loop proposed. In addition, a full-height model is also made. A total loss of flow accident is simulated in the prototype and both models with MARS-KS code. The simulation results show that the reduced-height model can better preserve the hydraulic similarity compared with the full-height model.

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