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# Systematic and exact scaling analysis of the single-phase natural circulation flow: The hydraulic similarity

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ABSTRACT

For the study of the hydraulic similarity in a single-phase natural circulation loop, the integral momentum equation is non-dimensionalized with respect to the initial flow kinematic energy of reference section, without intuitively specifying any reference parameters. By this mean, a unique hydraulic time scale, characterizing the system hydraulic response, is identified along with two dimensionless physical numbers: the dimensionless flow resistance number and the dimensionless gravitational force number. From the integral momentum equation, the mass flow rate at steady state is also obtained. The identified dimensionless parameters are then 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 was found for the first time that the cross sectional area scaling ratio should be related to the axial length scaling ratio. In addition, it is also found out that the relative cross-sectional area ratio should be preserved in order to preserve the flow resistances. Moreover, the scaling ratio for the number of the U-tubes was found to be unity if exact hydraulic similarity is pursued for the whole system. Three sets of scaling criteria for the design of a full-pressure model for a PWR are summarized in a table for different application. The accuracy and applicability of this proposed scaling method is demonstrated by proposing a simple loop and a PWR-like system, by scaling down the systems to get two corresponding models with this proposed scaling methodology, and by comparing the model results with their corresponding prototype results. Furthermore, the method for the evaluation of both system-level and local hydraulic scaling distortions are addressed.

## 1. Introduction

In the newly designed nuclear reactors, the passive safety systems are generally adopted to enhance the safety of nuclear reactors, such as the passive core cooling system (PXS) in the AP1000 (Schulz, 2006), the Passive Auxiliary Feedwater System (PAFS) in the APR+ (Song et al., 2010), the passive emergency shutdown system and a passive ADS (Automatic Depressurization System) in the Multi-Application Small Light Water Reactor (MASLWR) (Modro et al, 2003), and the Passive Residual Heat Removal System (PRHRS) in the SMART (Chang et al., 2002). 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 (Wright, 2007), a 1/4-height 1/2-time-scale reduced pressure integral systems facility, for the AP1000; the ATLAS-PAFS (Baeet al, 2014) for the APR1400; the MALWR facility (Reyes et al, 2007), a 1/3-length and 1/254-volume scale facility, for the MASLWR; the SMART-ITL (FESTA) (Park et al., 2014), a full-height and 1/49-volume scale facility, for the SMART. 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. Whereas, the natural circulation flow is predominated by the hydraulic characteristics of a system, the hydraulic similarity must be preserved between a scaled-down test facility and its prototype.

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The natural circulation system generally consists of a heat source, the connecting pipes and several heat sinks. A typical natural circulation integral nuclear reactor with some typical passive safety systems is shown in Fig. 1. Under an accident condition, the natural circulation in the primary loop will be established soon after the RCP (Reactor Coolant Pump) coastdown. With the activations of the passive safety systems, the passive safety system in combination with the coolant system makes up a natural circulation system.

Due to the importance of the scaling analysis in the nuclear safety research field, over the last several decades, a lot of researches have been done to develop the scaling methodologies for the mimic of the transients in a prototype with a reduced-size model. W. A. Carbiener et al. (Carbiener and Cudnik, 1969) proposed two sets of scaling criteria for the volumetric time-preserve scaling and linear time-reduced scaling, respectively, without giving any derivation. In 1979, A. N. Nahavandi et al. (Nahavandi et al., 1979) developed several sets of scaling criteria based on the turbulent finite differential equation, for three different cases: time-reducing scaling laws; time-preserving volumetric scaling laws; and time-preserving idealized model/prototype scaling laws. However, in this paper, the proposed method doesn't consider the interaction between the fluid and the flow boundary, it is inappropriate to apply it to the natural circulation flows, which are governed by the boundary conditions such as the boundary heat transfer and hydraulic forces. Nevertheless, it is applicable in cases where natural circulation is negligible. Such cases are the LBLOCAs (Large Break Loss Of Coolant Accidents), where forced convection flow dominates. In 1982, M. P. Heisler developed a set of dimensionless parameters for the scaling analysis of the natural convection in the liquid-metal faster breeder reactors (Michael, 1982). In this paper, for the first time, the hydraulic time scale scaling ratio was specified to be related to the length scaling ratio and velocity scaling ratio. Then, M. Ishii and I. Kataoka further extended M. P. Heisler's work to the single phase and two-phase natural circulation flows in the light water reactors (Ishii and Kataoka, 1984). Their work provides very applauding scaling criteria for the design of the scaled-down test facilities for the LWRs. Most newly constructed IET facilities are based on this scaling methodology along with the Hierarchical Two-Tiered Scaling (H2TS) Methodology (Zuber et al, 1984), such as the PUMA (Ishiiet al, 1998), the ATLAS (Baek et al, 2005), and the ACME (Chang et al, 2011). A comprehensive survey on the existing scaling methodologies and the main Integral Effect Test Facilities (IETFs) is compiled by S. K. Moon et al (Moon et al, 1998). Vijayan et al. derived a set of scaling parameters for single-phase natural circulation flow based on the momentum and energy conservation equations (Vijayan et al, 2000). The derived scaling parameters include the modified Grashof number $Gr_m$, the Stanton number, and a geometrical parameter $N_G$ which is only a function of the facility geometry. For the steady state conditions, they derived a correlation relating the steady state Reynolds number with the modified Grashof number. They further assessed the proposed correlation against their test data performed and other available data from the literature and showed good agreement.

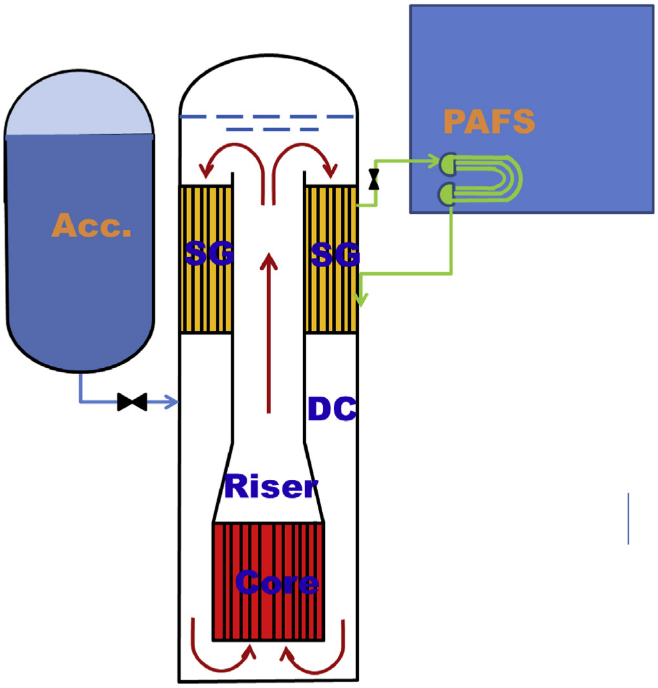

**Fig. 1.** The schematic of a natural circulation system equiped with passive safety systems.

The TH behaviors of a system can be analyzed at the system level. In the Ishii's scaling analysis, the authors indicate that the thermal-hydraulic behaviors can only be examined by the integral analysis of the thermal-hydraulic transport processes in the whole system. In order to develop meaningful similarity groups, it is essential to consider the overall system behaviors. In the development of the Ishii's scaling methodology, the integral momentum equation was employed in a similar way to the one used by M. P. Heisler for the scaling analysis of the fast breeder reactor. The integral approach was also taken by J. J. Jeong to study the non-uniform flow distribution in the SG (Steam Generator) U-tubes (Jeong et al, 2004). N. Zuber also suggested that the scaling issues should be solved by an integral structure and scaling methodology (Zuber et al, 1984).

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. First, an integral momentum equation is obtained by integrating the one-dimensional momentum equation along a closed loop. For the steady state condition, this integral momentum equation is rearranged to give an equation that relates the steady state system flow rate to the thermal condition and geometrical information of this system. For the transient analysis, the integral equation is non-dimensionalized with the initial flow kinematic energy of the reference section, without arbitrarily specifying any reference parameters. By this mean, two dimensionless parameters with physical meanings are identified along with a unique hydraulic time scale, which characterizes the system hydraulic response time. These dimensionless parameters are then applied to obtain the scaling criteria for a full-pressure reduced-size model for a PWR. The similarity of a certain phenomenon or characteristic is said to be preserved between a model and its prototype, as long as the corresponding dimensionless parameter associated with that phenomena or characteristic is made equal between them. The similarity analyses with these dimensionless parameters are then performed for each component of a PWR such as the pipe, the SG, and the core. Then, a set of scaling criteria are developed for a full-pressure model. If the developed set of scaling criteria is satisfied, the exact hydraulic similarity can be achieved between a model and its prototype. In the end, the methods for evaluating both system-level and local hydraulic scaling distortions are addressed.