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Research Paper

Heat transfer scaling analysis of the single-phase natural circulation flow system

Xin-Guo Yu [a,c,*], Ki-Yong Choi [a,b]

[a] University of Science and Technology (UST), 176 Gajeong-dong, Yuseong-gu, Daejeon 305-500, South Korea
[b] Korea Atomic Energy Research Institute, Dae-deok, Dae-ro 989-111, Yuseong-gu, Daejeon 305-353, South Korea
[c] School of Nuclear Sci. & Eng. (SNSE), North China Electric Power Univ. (NCEPU), Beinong lu 2, Changping, Beijing, China

HIGHLIGHTS

- A set of system-level and local heat transfer similarity numbers were proposed.
- The proposed dimensionless numbers can be applied to analyze the heat transfer similarity.
- Three set of scaling criteria for the design of reduced-size thermal systems were proposed.
- The tube inner diameter was found to be related to the length scaling ratio by $d_{iR} = \bar{l}_R^{0.75}$.

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ABSTRACT

In this study, the heating power in the heat source or the core decay power is proposed as the reference parameter for the scaling analyses. From the scaling analyses assuming quasi-steady state flow, three system-level dimensionless numbers for the thermal heat transfer were obtained: the dimensionless power rate number, the dimensionless HX heat transfer number, and the dimensionless heat loss number. Based on the three local heat transfer processes, the dimensionless HX heat transfer number is further broken down into three dimensionless local heat transfer numbers: the dimensionless HX tube internal convective heat transfer number, the dimensionless HX tube conductive heat transfer number, and the dimensionless HX tube external convective heat transfer number, with each representing local heat transfer similarity. Analogically, three dimensionless local heat loss numbers were also derived. With the obtained dimensionless numbers, the scaling criteria for exact HX heat transfer similarity were derived. It was found the tube inner diameter should be scaled down in terms of the tube length scaling ratio for exact heat transfer similarity. In addition, three sets of scaling criteria for a full-pressure model, the new scaling criteria (general), the new scaling criteria (ideal), and the new scaling criteria (practical), were proposed.

1. Introduction

Natural circulation flow can be found in many engineering applications and energy systems, such as in the solar systems, in the nuclear reactors, and in the geothermal and geophysical processes [1]. It is particularly important for the nuclear reactor safety, as it is the main mechanism for the operation of some passive safety systems and it is also one of the main means to remove the reactor core decay heat for the nuclear reactors. Since the natural circulation flow plays an important role in removing the reactor core decay heat, it is of considerate importance to study the thermal performance of a nuclear reactor. As the plant size becomes larger and larger from hundred MWt in the Shipingport nuclear power plant to thousands of MWt in the EPR^{tm} [2], it would become more and more infeasible to build a test apparatus of the same size as the power plant. One possible option is to scale down a system at a large scale to a smaller scale, for easier handling of the test apparatus and reduction of the cost. Many reduced-size test facilities have been designed and constructed for the reactor safety analysis over past several decades. Some of those, currently in operation, are the SNUF facility [3], the PKL facility [4], the ATLAS facility [5], the ROSA-V/LSTF facility [6] and the PMK-2 facility [7]. All the above-mentioned scaled-down test facilities were designed with different geometrical scaling ratio, either

* Corresponding author at: School of Nuclear Sci. & Eng. (SNSE), North China Electric Power Univ. (NCEPU), Beinong lu 2, Changping, Beijing, China.
E-mail address: yxg989@gmail.com (X.-G. Yu).

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full-height or reduced-height, and with different operating pressures, operated at either full pressure or reduced pressure with respect to their prototypes. Although the size of a system can be scaled up or down, not all the thermal-hydraulic processes or phenomena are faithfully preserved due to the unavoidable distortions of the complex phenomena involved. This is particularly the case in the field of nuclear reactor safety research. In most test facilities, reduced-scaled core power, rather than full scaled core power, is adopted at steady state condition and at initial short period of the transient due to both economic concern and scaling constraints, for example, in the ATLAS facility [8] and in the ROSA-V/LSTF [9]. In addition, the heat losses in the scaled down test facilities are generally much larger than that in their respective prototypes due to increased surface area of the structure per unit fluid volume, such as in the ROSA-V/LSTF [6] and in the ATLAS [10]. Moreover, higher secondary side pressure is allowed in the scaled-down test facilities such as in the ATLAS [11] and in the LSTF [12] to maintain the same temperature distribution in the primary loop as that in the prototype. Thus, several scaling parameters and operating conditions are usually distorted in the scaled model, resulting in some thermal scaling distortions in the modeling of the prototype's thermal-hydraulic behaviors. Therefore, the heat transfer scaling analysis should be performed for the single-phase natural circulation flow in a scaled-down model test facility in order to preserve the heat transfer similarity and the heat loss similarity.

As the natural circulation flow is driven by the buoyancy force while the buoyancy force is affected by the heat transfer in the heat exchanger, it is of primary importance to preserve the heat transfer similarity in a natural circulation system. The natural circulation flow in a natural circulation flow system is strongly affected by the thermal transport processes. Therefore, it is important to preserve the thermal similarity between a scaled-down test facility and its prototype. From this respect, a robust scaling methodology must be developed and employed to ensure the thermal transport similarity between a model facility and its prototype, so that the natural circulation phenomena in the prototype can be reproduced in the model facility. Plenty of scaling laws have been proposed in the past, devoted to produce the thermal-hydraulic phenomena in a prototype with a model facility. Carbenier [13] proposed two sets of scaling parameters: the volumetric scaling in which the time scale is preserved in the model facility and the linear scaling in which the time scale is reduced in the model facility. The authors commend that the volumetric scaling is suitable for the simulation of LBLOCA where flashing is occurring, and the linear scaling might be applicable for cases where flashing is not expected. Most of the scaled-down test facilities built so far are based on this volumetric scaling law. Heisler developed a set of dimensionless parameters for the scaling analysis of the natural convection in the liquid-metal faster breeder reactors [14]. The author developed a set of scaling parameters for liquid-metal fast breeder reactor natural convection shutdown heat removal test facilities. The proposed dimensionless numbers for similarity analyses include the Richardson number, the Stanton number, the Biot number, the Dammkohler volumetric heat generation number Q_{si}, the dimensionless friction loss number Fl, and a dimensionless time scale. It was found that the use of the water to simulate the sodium and NaK can lead to inevitable scaling distortions. The author also recommends using the prototypic fluids sodium and NaK, rather than other fluids, for a liquid-metal test facility. Ishii derived sets of scaling criteria for single-phase and two-phase natural circulation flow in which the velocity scale is related to the length scale to preserve the gravitational force similarity. By adopting this approach, it might be feasible to simulate the natural circulation flow with a reduced-height model facility [15]. Later, Ishii and his coauthors applied the three-level scaling approach and the derived scaling criteria to the design of the PUMA facility [16]. Vijayan et al. derived a set of scaling parameters for single-phase natural circulation flow based on the momentum and energy conservation equations [17]. The derived scaling parameters include the modified Grashof number, the Stanton number, and the Nusselt number. 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 on three natural circulation loops with different inner diameters and showed good agreement. They also correlated some natural circulation data in the open literatures and found good agreement.

Although many scaling methods are available, few addressed the scaling issues related to the heat transfer in the HX and the heat loss, which are particularly important for the natural circulation flow. It is known that the system heat loss is generally distorted in a scaled-down test facility, but there is a lack of meaningful dimensionless numbers for the evaluation of such heat loss scaling distortion. If the system heat loss similarity in a scaled-down model facility is to be seek, the dimensionless number for the heat loss similarity should be also given. The heat transfer similarity in the HX is also slightly distorted in the ATLAS test facility as observed in the RELAP code simulation results [10]. To preserve the heat transfer similarity, the proper dimensionless HX heat transfer number should be available for the derivation of the scaling ratios. In present study, a new scaling methodology for exact preservation of the HX heat transfer similarity and for the heat loss similarity, is proposed. And, it can also be applied to evaluate the heat loss scaling distortion the system and the heat transfer scaling distortion in the HX. A large part of the work in this paper is based on the author's previous research [18]. As the natural circulation flow is self-driven, it can be viewed as the quasi-steady state flow. Assuming the quasi-steady state flow for the single-phase natural circulation flow, three system-level dimensionless numbers, the dimensionless power rate number, the dimensionless HX heat transfer number, and the dimensionless heat loss number, were obtained. Each system-level dimensionless number characterizes its corresponding global thermal heat transfer similarity. From the system-level dimensionless HX heat transfer number, three dimensionless local heat transfer numbers: the dimensionless HX tube internal convective heat transfer number, the dimensionless HX tube conductive heat transfer number, and the dimensionless HX tube external convective heat transfer number, were proposed. Likewise, three dimensionless local heat transfer numbers for the heat loss were also obtained. Three sets of scaling criteria for exact preservation of thermal similarity for the single phase natural circulation are then derived by setting these dimensionless parameters in a full-pressure model equal to those in the prototype. Three sets of scaling criteria for a full-pressure model developed are named the new scaling criteria (general), the new scaling criteria (ideal), and the new scaling criteria (practical), respectively.

2. Derivation of the thermal similarity parameters

In general, a natural circulation system consists of a heat source and the heat sinks. The nuclear reactor with the RCPs coasted down can also be viewed as a NC system. In the heat source, the fluid is heated up, while in the heat sinks, the fluid is cooled. The heating and cooling processes during the fluid natural circulation flow establish a density difference between the heat source and the heat sink, which then drives the natural circulation flow. As long as there is no abrupt change in the heating power and in the fluid conditions of the heat sinks, the natural circulation flow might be viewed as the quasi-steady sate flow. For the scaling analysis of the single-phase natural circulation flow, the coolant in the