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Scaling Criteria for Modeling Natural- and Forced-Convection Loops

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Nuclear reactor safety regulations have required extensive thermal-hydraulic testing of simulated reactor systems and components. In view of the inherent difficulties associated with full-scale testing, scale models for prototype systems have been extensively used to predict the behavior of nuclear reactor systems during normal and abnormal operations as well as under accident conditions. Several studies[1-5] have been performed to establish similarity relations between a prototype and scale model. The development in each of these investigations is limited to the power to volume scaling and is based on single-phase flow conservation equations that cannot reflect the phenomena associated with the two-phase flow systems. The available models to develop similarity criteria for two-phase flow systems have been reviewed by Ishii and Jones,[6] and the similarity analysis for a two-phase flow system has been carried out by Ishii and Zuber,[7] Zuber,[8] and by Ishii and Kataoka.[9] Based on the analysis in Ref. 9, it is the purpose of the present study to develop scaling criteria for a forced and natural circulation loop under single- and/or two-phase flow conditions, and to apply the criteria to obtain the preliminary conceptual design parameters for the B&W 2 x 4 loop system. The 2 x 4 loop scaled system contains representative components of all thermal-hydraulic systems considered important in performing tests to obtain data representative of the response of the prototype plant. This system includes an electrically powered reactor vessel simulator, and two loops with representative hot leg, once through steam generator, and two active cold legs with pumps.

For a single-phase case, the mass, integral momentum, and energy equations in one-dimensional area-averaged forms are used to identify the

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DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED important similarity groups. For a special case of a scale model with the same fluid under same system pressure, it has been concluded that the following conditions should be satisfied

$$u_R = \dot{q}_R''' = \ell_R \qquad (1)$$

and

$$\delta_R = d_R = 1 \text{ (heat transfer sections)} \qquad (2)$$

where u, ℓ, $\dot{q}'''$, δ, and d are the velocity, length, power density, conduction depth, and hydraulic diameter, respectively. The subscript R denotes the ratio of the value for a model to that of the prototype. Under these conditions, the real time scaling is established, i.e., $t_R = 1$. In addition to the above three constraints, the geometric and dynamic similarity conditions are required. Thus

$$(\ell_i/\ell_o)_R = (a_i/a_o)_R = 1 \qquad (3)$$

and

$$F_{iR} = \{(f_i/d_i)(\ell_i+\ell_{ei}) + K_i\}_R = 1 \qquad (4)$$

where the subscripts i and o identify the ith component and reference value in the loop, whereas a, f, ℓ_e, and K are the flow area, friction factor, equivalent length for minor losses distributed over the component, and the singular loss coefficient defined at the inlet and exit of the component, respectively.

Among the above constraints, the most severe condition in terms of the thermal-hydraulic simulation is imposed by Eq. (4), because in a scaled model the hydraulic diameter can be much smaller. From a series of parametric study based on TMI Unit-2 plant, it became clear that the hot leg simulation imposes the strongest constraint. Once the necessary condition for the hot leg is obtained, other sections are easily adjusted by increasing K value appearing in Eq. (4). Based on the hot leg simulation, the solution to the similarity criteria under single-phase flow condition can be approximated by

$$\ell_R = 15.24\ a_R^{0.7024} \tag{5}$$

It is to be noted here that two-phase flow cannot be simulated with Eq. (5).

For a two-phase flow case, the similarity groups are obtained from perturbation analysis based on the one-dimensional drift-flux model. Conditions imposed by these groups are evaluated, and it was concluded that the following conditions are necessary for two-phase flow simulation:

$$u_R = \sqrt{\ell_R} \tag{6}$$

and

$$\dot{q}_R''' = 1/\sqrt{\ell_R} \tag{7}$$

Under these conditions, the real time simulation cannot be achieved. The time is distorted by

$$t_R = \sqrt{\ell_R} \tag{8}$$

This indicates that the time runs faster in the scaled model by a factor of $\sqrt{\ell_R}$. In addition to the above conditions, the geometric and dynamic similarity conditions expressed by Eqs. (3) and (4), respectively, are required for a proper scaling. Finally, it was shown that these requirements also satisfy the single-phase scaling criteria for the distorted time simulation.

Based on the TMI Unit-2 plant as a prototype, the solution to the similarity requirements is presented in Fig. 1. It can be approximated by

$$\ell_R = 10.0\ a_R^{0.658} \tag{9}$$

for the natural circulation simulation loop, and

$$\ell_R = 10.23\ a_R^{0.623} \tag{10}$$

for the forced convection simulation loop.

The bounded area between two curves in Fig. 1 indicates the length ratio range over which the solution should be sought if the model is to be built for the simultaneous simulation of forced and natural circulations. For example, for a volume ratio of $V_R = a_R \cdot \ell_R = 1/815$ the length ratio suitable for both forced and natural circulation simulation is given by $0.270 < \ell_R < 0.312$.

The specific results of similarity criteria obtained from the proper conservation equations are presented here for a natural and forced convection circulation loops under single- and/or two-phase flow condition. It is demonstrated that a solution in the form of $\ell_R = f(a_R)$ can be achieved for both cases. The explicit form of this function depends on the prototype system. The solutions are presented for TMI Unit-2 plant.

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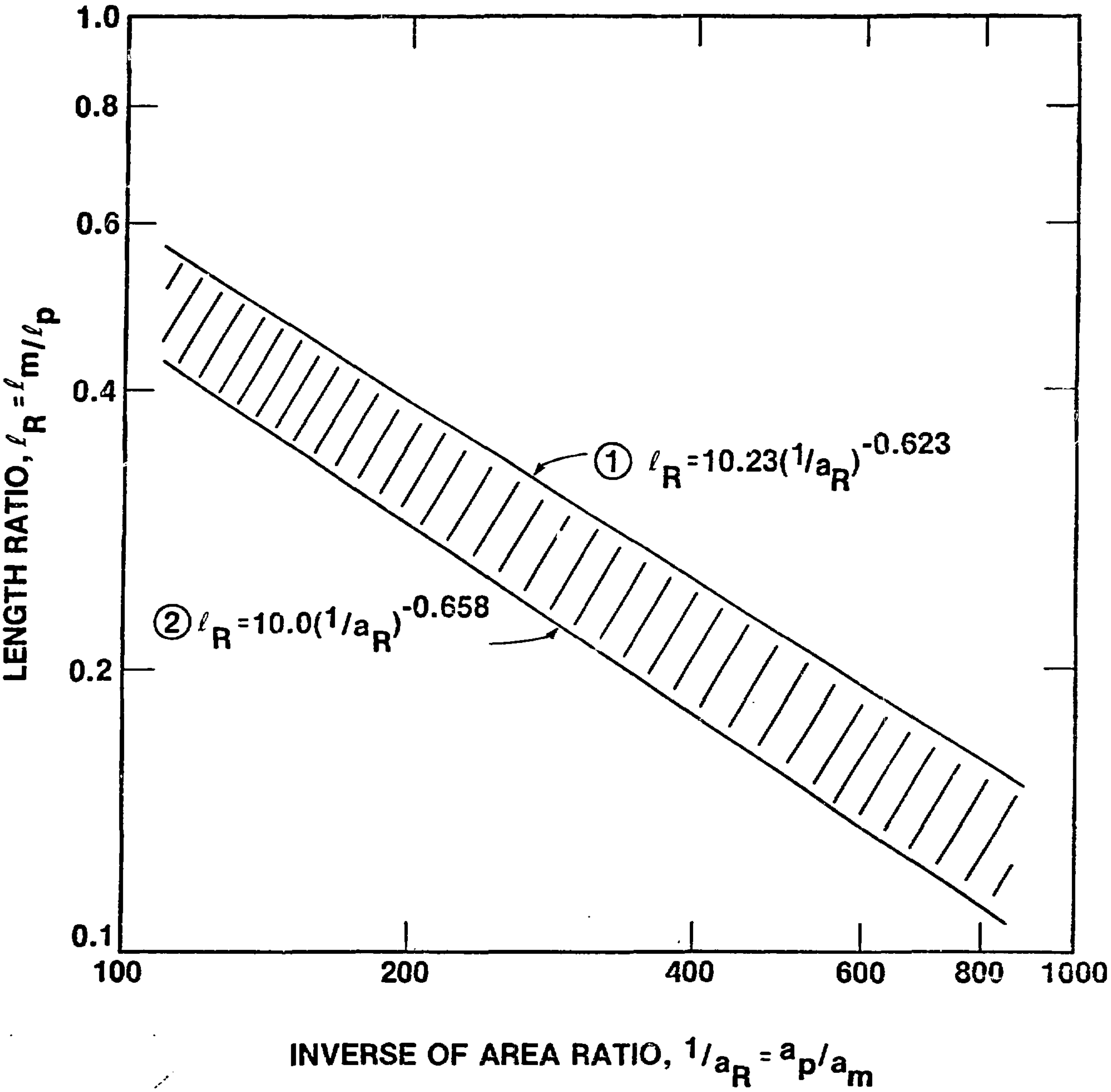

Fig. 1. Comparison of Forced and Natural Circulation Systems, Time-Distorted Scaled Model Requirements

1. Forced Convection
2. Natural Convection