Proceedings of the Korean Nuclear Society Spring Meeting

Pohang, Korea, May 1999

Comparison of an Integral Response Scaling Method with Ishii's Scaling Method and its Validation Using RELAP5/MOD3.2

Hyoung Tae Kim and Hee Cheon NO
Korea Advanced Institute of Science and Technology

Chang Kyung Sung and Sang Jun Ha
Korea Electric Power Research Institute

Abstract

An integral response scaling method for a reduced-height test facility is suggested and the scaling laws derived from it are compared with Ishii's scaling. In the present scaling method it turns out that flow velocities in the vertical channel and through the break area or injection area should be preserved.

RELAP5/MOD3.2 code calculations of pot-boiling, blowdown, heat transfer in Steam Generator(SG) and off-take are conducted for the validation of the present scaling method. Four scaled-down models are designed based on the present method and Ishii's scaling method given length and area scales of 1/5 and 1/100, respectively. RELAP5/MOD3.2 calculations show that the scaled-down model based on the present scaling method well maintains the similarity of the nondimensional mixture level in pot-boiling, the nondimensional pressure in blowdown and the heat transfer coefficient in SG.

1. Introduction

In order to understand thermal-hydraulic phenomena in nuclear power plants, many integral and separate-effect test facilities have been constructed. In view of the inherent difficulties associated with a full-scale test facility, many scaling laws for integral test facilities are suggested by Larson[1], Ishii and Kocamustafaogullari[2], Ishii and Katsoka[3], Reyes[4], and NO[5]. The scaling laws most commonly used for modeling nuclear reactor systems are linear scaling[6], volume scaling[6], and several sets of single- and two-phase scaling criteria derived by Ishii[3,7].

Using three-dimensional conservation equations along with the equations of state, Nahavandi et al.[6] derived two sets of scaling laws: linear scaling for time-reduction scaling law and volume scaling for time-preserving scaling law. In the linear scaling u_R and g_R are preset to be scaled as l_R/τ_R and l_R/τ_R^2 according to their dimensions, respectively. The final scaling requirements are $\tau_R = l_R$ and $\dddot{q}_R \tau_R = 1$. Then, the velocity and gravity scaling requirements become 1 and $1/l_R$, respectively. Note that gravity scaling can be highly distorted when l_R is much smaller than 1. This distortion comes from the presetting of the gravity scaling requirement according to its dimension. The linear scaling method is valid for the scaling of a scaled-down facility with negligible gravity contribution such as forced convection and blowdown. In the volume scaling u_R and g_R are preset in the same way as in the linear scaling but with the time-preserving scaling requirement, $\tau_R=1$. The final scaling requirements are derived as $l_R=1$ and $q'''_R=1$, respectively. Then, both of the velocity and gravity in the scaled-down model are preserved. Therefore, gravity scaling is preserved. However, the volume scaling is valid for the full-height and full-pressure experiment only.

Ishii presents a set of scaling requirements which can be applied to a reduced-height and reduced-pressure experimental facility. Ishii's scaling laws highly depend on the following relationship coming from the scaling law of the Froude number:

$$u_R=\sqrt{l_R}. \tag{1}$$

With the above relationship, time and the volumetric heat generation rate are scaled as follows:

$$\begin{aligned} &\tau_R=l_R/u_R=\sqrt{l_R} && \text{for time,} \\ &q'''_R=1/\tau_R=1/\sqrt{l_R} && \text{for volumetric heat generation.} \end{aligned} \tag{2}$$

If a full-height model is used, Ishii's scaling becomes identical with the volume scaling. The above three scaling laws are summarized and examined by Kiang[8]. In order to maintain similarity, Ishii's velocity scaling law, Eq. (1) requires the reduced velocity for a model with reduced height. The reduced velocity scaling causes scaling problems for transients such as pot-boiling and blowdown which requires maintaining the constant velocities for both of the prototype and the model. Here, the integral response scaling method for a reduced-height test facility is suggested and the scaling laws derived from it are compared with those from Ishii's ones for pot-boiling, blowdown and heat transfer in SG using RELAP5/MOD3.2[9].

2. Integral Response Scaling Method for Full-pressure Reduced-height Test Facility

The following integral response function[5] is expressed in terms of the nondimensional variables and nondimensional scaling parameters[10], which represents the nondimensional solutions of the nondimensional integral governing equations with boundary and initial conditions integrated over the time period from the initial time to a specified time:

$$\begin{aligned} \Psi^* = \int_0^{t^*} f(& N_{ax}, N_{mom}, N_{th}, N_{x}, N_{gc}, N_T, N_{cl}, N_{co}, N_{sd}, N_{Pco}, N_{pump}, N_g, \\ & N_{Qco}, N_{Qcore}, N_h, N_\rho, N_{sub}, N_\phi, N_{Bi}, \overline{\Gamma_g^*}, \dot{Q}^*_{co}, Q^*_{core}, \Delta P^*_{co}, \Delta P^*_p, u^*_{gc}, \dot{Q}^*_s) dt^*, \end{aligned} \tag{3}$$

where Ψ^* represents $M^*, M^*_g, M^*_{sc}, h^*, W^*, V^*_{SL}, z^*_{sub}$, or T^*_s .

To satisfy the similarity between the model and prototype system, that is,

$$[\Psi^*]_R=\Psi_{model}/\Psi_{prototype}=1. \tag{4}$$

The similarity criteria for different fluids at different pressures are extremely complicated[5]. In this paper a scaled-down model with the same solid material and the same fluid is considered for a significant amount of simplifications.

Let us set up the basic scaling relationships among velocity, length, area, power, and time given the length and area scaling ratios, l_R and a_R. We have the following scaling relationships:

Mixture level: $[u_0/u_{g0}]_R=1 \rightarrow [u_0]_R=1$.

Momentum: $[l_r/u_0^2]_R=[f_0 l_0/D+K_0]_R$.

Mass: $[W_0]_R=[u_0A_0]_R=[u_0M]_R=[Q_0]_R \rightarrow [u_0]_R=[Q_0/A_0]_R=[Q_0/M]_R$

$\rightarrow [Q_0]_R=[M]_R$ if $[u_0]_R=1$.

Energy:

in the heated fuels: $[Nl_0Dq']_R=[Q_0]_R \rightarrow [Nl_0q']_R=[Q_0]_R$, if $[D]_R=1 \rightarrow [l_0q']_R=1$,

in the SG tubes: $[Nl_0u_0^{0.8}]_R=[Q_0]_R \rightarrow [N]_R=[Q_0]_R/[l_0]_R$, if $[u_0]_R=1 \rightarrow [l_0]_R=1$.

Counter-current flow limitation and horizontal stratification requirements in horizontal pipes:

$$[u_0^2/D]_R=1\,. \tag{5}$$

For the reduced-time scaling in the horizontal pipe the diameter of the horizontal pipe is scaled as follows:

$$[W]_R=[\rho u_0D^2]_R=[Q]_R \rightarrow [D]_R=[Q_0{}^{2/5}]_R. \tag{6}$$

Bubbly-slug transition and counter-current flow limitation in vertical channels:

$$[D]_R=1, \quad [u_0]_R=1\,. \tag{7}$$

Time scaling:

$$[\tau_0]_R=[l_0/u_0]_R. \tag{8}$$

The simple way to simultaneously satisfy the above equations is to build the full-height full-pressure facility. If reduced height is inevitable, the scaling laws from mixture level, mass, and energy are satisfied through $[u_0]_R=1$ in the vertical channels and $[u_0^2/D]_R=1$ in the horizontal pipes, and the following scaling law from momentum should be satisfied:

$$[l_0]_R=[f_0 l_0/D+K_0]_R. \tag{9}$$

Then, the time scaling law becomes the following time-reduced one:

$$[\tau_0]_R=[l_0]_R. \tag{10}$$

Note that $[u_0]_R=1$ is required for the break area and injection area in the blowdown transient and for the vertical fuel channels in the pot-boiling transient except for the horizontal pipes. The above basic scaling relationships are described with those from other scaling methods for comparison in Table 1. In Table 1 length and velocity scaling parameters are divided into two; horizontal pipes and vertical channels. The present method uses different scaling ratios for the two cases while Ishii's scaling does the same ones. This difference leads to different time, flow rate, and power scaling ratios for the two scaling methods. Let us compare the two scaling methods using the best estimation code, RELAP5/Mode3.2. in order to see which methods better describe the similarity between the prototypic system and the scaled-down models.

3. Validation Using RELAP5/MOD3.2

3.1 Scaling for pot-boiling

If the water inventory is reduced so that the two-phase mixture level drops below the top of the active core, it may undergo the core uncovery and heatup process[11]. This process is called pot-boiling. The two-phase mixture level is generally marked as a discontinuity in the axial void distribution[12]. For the view of safety we need to know the two-phase mixture level during the pot-boiling phase.

The core boil-off with downcomer feed is schematically shown in Fig. 1. NO and Ishii[13] generated the following nondimensional parameters to describe the nondimensional two-phase mixture level:

$$N_{pch}=\Gamma\tau/\rho_g,\ \ N_\rho=\rho_g/\rho_f,\ \ N_{sub}=\Delta h_{sub}/h_{fg},\ \ N_d=u_0/u_{gj}. \tag{11}$$

For the same pressure conditions Ishii's scaling method generates the same scaling laws for the first three parameters in Eq. (11) as the present method except that the drift flux parameter, $[N_d]_R$ is $\sqrt{l_R}$ and 1 for Ishii's method and the present method, respectively.

The recently released code version (RELAP5/MOD3 version 2.1.2) is used for the investigation of scaling effects[13] related to pot-boiling. Let us construct RELAP5/MOD3.2 nodal models on the basis of the present model and Ishii's scaling. A reference model representing a reactor vessel of Korea Next Generation Reactor(KNGR)[14] is nodalized in Fig. 2. The scaled-down models are initiated at the same pressure but with the scaled-down power and inlet flow. The time variations of the nondimensional mixture level calculated from RELAP5/MOD3.2 are shown in Fig. 3. An initial increase in the mixture level represents level swell due to the rapid power increase. The simulations end when the mixture level reaches the top of the active core.

The variation of the nondimensional mixture level in the scaled-down model generated by the present scaling model well agrees with that in the prototype. However, the mixture level in the model generated by Ishii's scaling method is lower than that in the prototype. The failure of Ishii's scaling is due to the distortion of the velocity scaling. The time variations of the drift-flux parameter by the scaled-down models are shown in Fig. 4. The trend of the model produced by the present method is in good agreement with that of the prototype. This preservation of the drift-flux parameter produces the same void fraction as that of the prototype as shown in Fig. 5. The void fraction in the model produced by Ishii's scaling method is lower than that by the prototype until the mixture level starts to form in the volume. The scaled-up of the drift-flux parameter results in the lower void fraction and more rapid mixture drop in the model generated by Ishii's scaling than those in the prototype. It can be concluded that power and inlet flow should be scaled as the same as area scale to preserve the velocity in the scaled-down model.

3.2 Scaling for Blowdown

Consider a simple system in which subcooled water at hight pressure is discharged from a reactor vessel through a break of the Direct Vessel Injection(DVI) line as shown in Fig. 6.

The nondimensional form of governing equations for the process are as follows:

Mixture mass balance:

$$\left(\frac{M_0}{W_{b0}\tau_b}\right)\frac{dM^*}{dt^*}=-W_b^*, \tag{12}$$

where subscript 0 denotes the initial condition, M is the total system mass, and W_b is the discharge flow rate through a break. Lee and NO(1992)[15] showed that the nondimensional parameters in Eq. (12) are the main scaling parameters for the simulation of the nondimensional pressure response in a blowdown transient. These nondimensional variables are:

$$t^*=\frac{t}{\tau_b},\quad W_b^*=\frac{W_b}{W_{b0}},\quad P^*=\frac{P}{P_0}. \tag{13}$$

To obtain the nondimensional time and break flow in Eq. (13) the initial break flow, W_{b0} is calculated as

$$W_{b0}=A_bC_D\sqrt{\Delta P_0\rho_0}. \tag{14}$$

Then t^* and W_b^* are correlated with the following relations:

$$t^*=\left(\frac{A_bC_D\sqrt{\Delta P_0\rho_0}}{M_0}\right)t,\quad W_b^*=\frac{W_b}{A_bC_D\sqrt{\Delta P_0\rho_0}}. \tag{15}$$

The scaling parameters of depressurization are related to the global geometry such as total system volume and break size. From Eq. (15) the time constant ratio of the scaled-down model is

$$[\tau_b]_R=\left[\frac{M_0}{A_b}\right]_R=[l]_R. \tag{16}$$

Now, we can see that the time constant ratio of the present model agrees with that of Eq. (16).

The trends of the nondimensional pressure and break flow from RELAP5 calculations are shown in Figs. 7 and 8. The rapid decrease of pressure is initially observed following the sudden drop[16] of the pressure up to about half of the initial value as expected. The pressure behavior of the present model well agrees with that of the prototype. An earlier decrease in pressure in Ishii's scaling model is due to velocity scaling distortion. According to Ishii's scaling method a break area should be scaled as $a_R\sqrt{l_R}$ to maintain the velocity scale at the break. However, if the total break of the pipe such as the cold leg break or the hot leg break takes place, the break area is the same as the flow area. That is why the pressure more rapidly reduces in the model designed by Ishii's scaling method than that in the prototype. The only way in which break scaling is set to be the same as flow area scaling is to set up time scaling as $\tau_b=l_R$ in the same way in the present scaling method, preserving the velocity at the break area in the scaled-down model.

3.3 Scaling for heat transfer in SG

RELAP5/MOD3.2 code calculations of two heat transfer mechanisms for single-phase convection and reflux condensation in SG are conducted for the validation of the present scaling method.

Figure 9 shows the nodalization of the primary and secondary sides of SG.

First, single-phase convection in the SG model is calculated by RELAP5/MOD3.2 to validate the present scaling method. Figure 10 shows the steady-state temperatures both in the primary and secondary side of the SG. The tube numbers, 1, 2, and 14 indicate the inlet plenum, first cell of the U-tube, and the outlet plenum of SG, respectively. Since the flow velocity in the SG U-tube and its diameter are preserved in the present model, both Heat Transfer Coefficient(HTC) and temperature difference between SG primary and secondary sides are preserved. Therefore, with given secondary temperature the distribution of the primary temperature by the present model well agrees with that by the prototype as shown in Fig. 10. Figure 11 also shows that HTC by the present model is nearly the same as that by the prototype. The convective HTC by Ishii's model is lower than that by the prototype because the flow velocity is scaled-down in this model.

Next, reflux condensation in the SG model is calculated by RELAP5/MOD3.2.

The condensation HTC of Ishii's model is higher than that of the prototype, while the HTC of the present model well agrees with that of the prototype. The distortion of the HTC of Ishii's model comes from the lower film Reynolds number than that of the prototype. The film Reynolds number is not preserved due to the reduced steam velocity in Ishii's model. As the condensate film grows toward both the SG inlet and outlet plenums, the condensation HTCs in Fig. 12 show a peak on the top of the SG U-tubes.

Condensation of steam and non-condensable mixture is also calculated by RELAP5/MOD3.2. For this simulation steam with the air mass fraction of 0.03 is injected for 600 sec in the reference model. The initial pressure is 1.0 MPa but continuously increased as the air is accumulated in the SG U-tubes. From Fig. 13 we can see that the trend of the degradation of condensation HTC by the present model is the same as that by the prototype.

We can conclude from these simulations that the preservation of the flow velocity in U-tubes is essential to preserve the heat transfer rate in the prototype.

4. Conclusions

In the present scaling method it turns out that flow velocities in the vertical channel, and through the break area or injection area should be preserved.

RELAP5/MOD3.2 calculations show that the scaled-down model based on the present scaling method well maintains the similarity of the nondimensional mixture level in pot-boiling, the nondimensional pressure in blowdown, the HTC in SG and the discharge quality in off-take.

We can conclude that it is essential to set up time scaling as $\tau_R = l_R$ and the same break area scaling as flow area scaling in the same way in the present scaling method, preserving the velocity at the break area in the scaled-down model.

References

1. T. K. Larson, "Scaling Criteria and an Assessment of Semiscale Mod-3 Scaling for Small Break Loss-off-coolant Transients," EG&G Idaho, EGG-SEMI-5121 (March 1980).
2. M. Ishii and G. Kocamustafaogullari, "Scaling Criteria for Two-phase Flow Natural and Forced Convection Loop and their Application to Conceptual 2×4 Simulation Loop Design," NUREG/CR-3420 (May 1983).
3. M. Ishii and I. Kataoka, "Scaling Laws for Thermal-hydraulic System under Single Phase and Two-phase Natural Circulation," *Nucl. Eng. Des*., **81**, 411 (1984).
4. J.N. Reyes, "Low-pressure Integral Systems Test Facility Scaling Report," WCAP-14270 (Jan. 1995).
5. S.I. Lee and Hee Cheon NO, "An integral Response Scaling Method for a Scaled-Down Test Facility Simulating SB-LOCA in a Passive PWR," NURETH-6, **2**, 1387, Grenoble, France (Oct. 1993).
6. A.N. Nahavandi, F.S. Castellana, and E.N. Moradkbanian, "Scaling Laws for Modeling Nuclear Reactor System," *Nucl. Sci. Eng.*, **72**, 75 (1979).
7. M. Ishii, S.T. Revanka et al., "Scientific Design of Purdue University Multi-Dimensional Integral Test Assembly(PUMA) for GE SBWR," NUREG/CR-6309 (March 1996).
8. R.L. Kiang, "Scaling Criteria for Nuclear Reactor Thermal Hydraulics," *Nucl. Sci. Eng.*, **89**, 207 (1985).
9. K.E. Carlson, R.A. Riemke, S.Z. Rouhani, R.W. Shumway, and W.L. Weaver, "RELAP5/MOD3 Code Manual," Vol. **1**, NUREG/CR-5535, EGG-2596, EG&G Idaho, Inc. (June 1995).
10. Hee Cheon NO and Hyoung Tae Kim, "An Integral Response Scaling Method for Reduced-Height Test Facilities and its Comparison with Ishii's Scaling Method," KEPCO Tech. Report, TR.97NJ25.E1988.88 (Dec. 1998).
11. Hee Cheon NO and M. Ishii, "Scaling Study of In-core Boil-off and Heating Process," *Nucl. Eng. Des.*, **143**, 265 (1993).
12. K.H. Sun, R.B. Duffey and C.M. Peng, "The Prediction of Two-Phase Mixture Level and Hydrodynamically-Controlled Dryout Under Low Flow Conditions," *Int. J. Multiphase Flow*, Vol. **7**, No. 5, 521 (1981).
13. T.K. Larson and R.A. Dimenna, "Preservation of Natural Circulation Similarity Criteria in Mathematical Models," *Nucl. Sci. Eng.*, **100**, 21 (1988).
14. S.H. Chang and Hee Cheon NO et al., "Power Plant Design: Korea Looks Beyond the Next Generation," *Nuclear Engineering International*, Vol. **42**, 12 (Feb. 1997).
15. S.I. Lee and Hee Cheon NO, "A Simple Analytical Scaling Method for a Scaled-Down Test Facility Simulating SB-LOCAs in a Passive PWR," M.S. Thesis, Dept. of Nucl. Eng., Korea Advanced Institute of Science and Technology(KAIST) (1992).
16. V.E. Schrock, S.T. Revankar, R. Mannheimer, and C-H. Wang, "Small Break Critical Discharge -The Roles of Vapor and Liquid Entrainment in a Stratified Two-Phase Region Upstream of the Break," NUREG/CR-4761, LBL-22024 (Dec. 1986).

Table 1. Comparison of Scaling Parameters of Several Scaling Methods

Parameter	Linear Scaling	Volume Scaling	Ishii's Scaling	Present Method
Axial length	l_R	1	l_R	l_R
Flow area	l_R^2	a_R	a_R	a_R
Pipe diameter(H)	l_R	$a_R^{2/5}$	$a_R^{1/2}$	$a_R^{2/5}$
Channel diameter(V)	1	1	1	1
Heated fuel length	l_R	1	l_R	l_R
SG tube length	l_R	1	l_R	1
Break area	l_R^2	a_R	$a_R\, l_R^{1/2}$	a_R
Injection area	l_R^2	a_R	$a_R\, l_R^{1/2}$	a_R
Velocity(V)	1	1	$l_R^{1/2}$	1
Velocity(H)	1	1	$a_R^{1/4}$	$a_R^{1/4}$
Flow rate	l_R^2	a_R	$a_R\, l_R^{1/2}$	a_R
Core power	l_R^2	a_R	$a_R\, l_R^{1/2}$	a_R
Power/Volume	l_R^{-1}	1	$l_R^{-1/2}$	l_R^{-1}
# of heated tubes	-	a_R	$a_R\, l_R^{-1/2}$	a_R
Time	l_R	1	$l_R^{1/2}$	l_R

* **H** : **H**orizontal pipe

V : **V**ertical channel

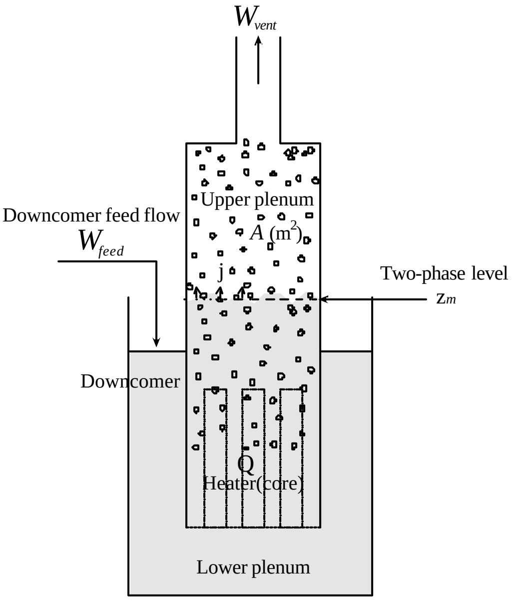

Fig. 1. Schematic of a reactor vessel during pot-boiling with downcomer feed and steam venting.

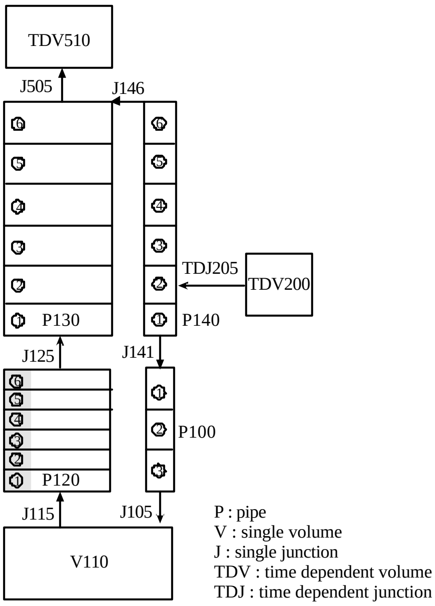

Fig. 2. RELAP5 nodalization of pot-boiling system.

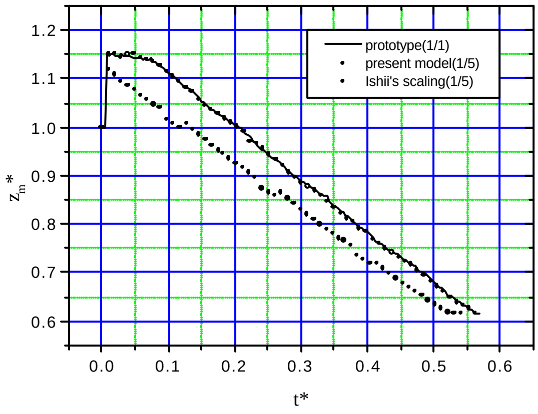

Fig. 3. Comparison of variations of nondimensional two-phase mixture level.

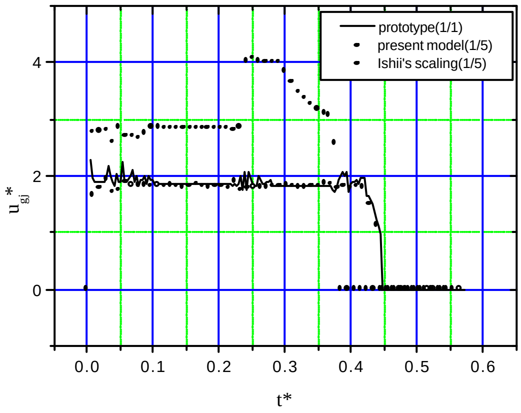

Fig. 4. Comparison of variations of the drift-flux parameter.

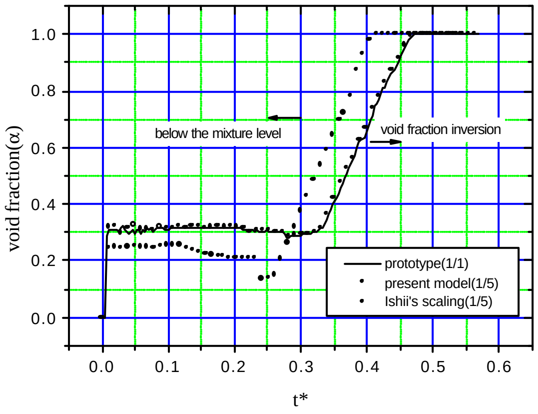

Fig. 5. Comparison of variations of void fraction in the nodal volume, P130-02.

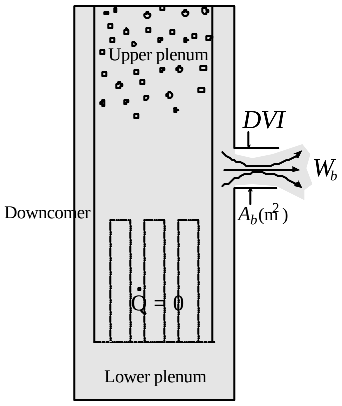

Fig. 6. System configuration of blowdown simulation.

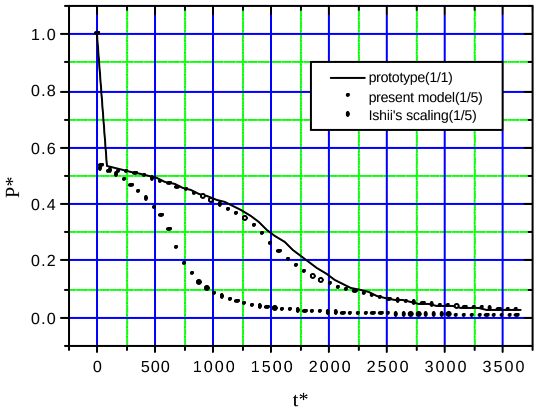

Fig. 7. Comparison of nondimensional pressure transients.

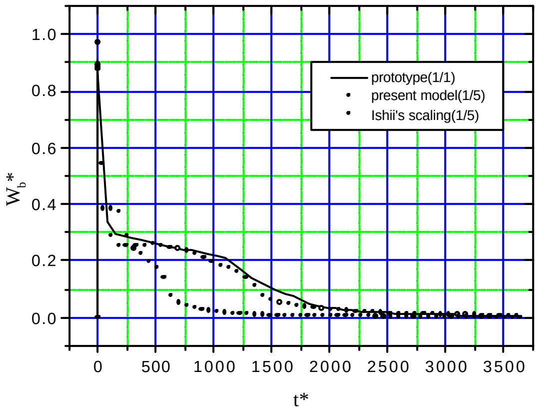

Fig. 8. Comparison of nondimensional break flows.

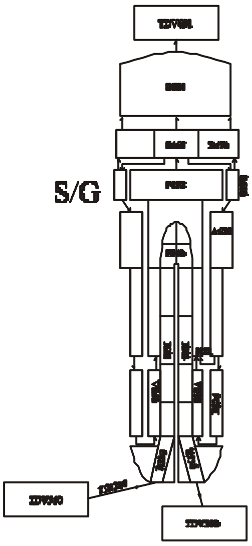

Fig. 9. RELAP5 nodalization of SG.

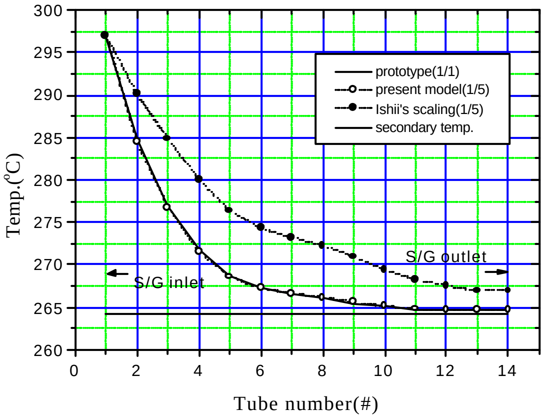

Fig. 10. Comparison of steady-state temperatures in the SG primary side.

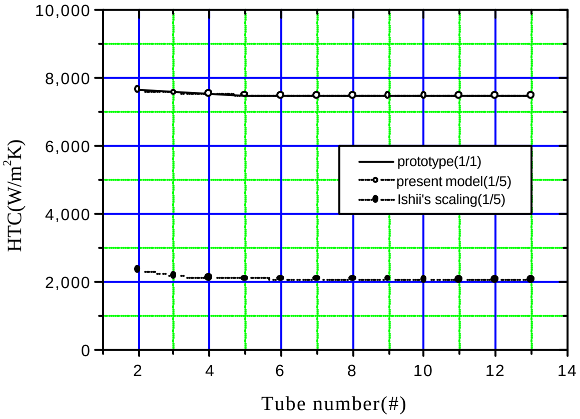

Fig. 11. Comparison of convective HTCs in the SG primary side.

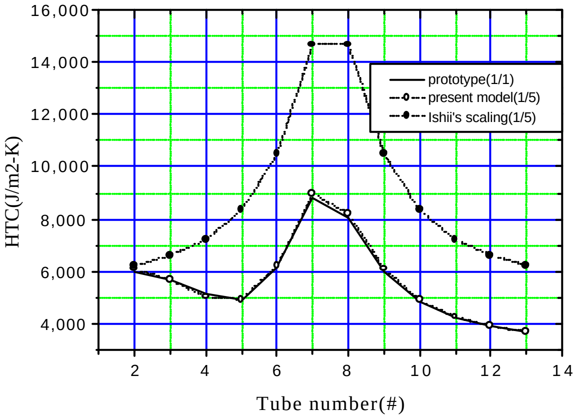

Fig. 12. Comparison of reflux condensation HTCs in the SG primary side.

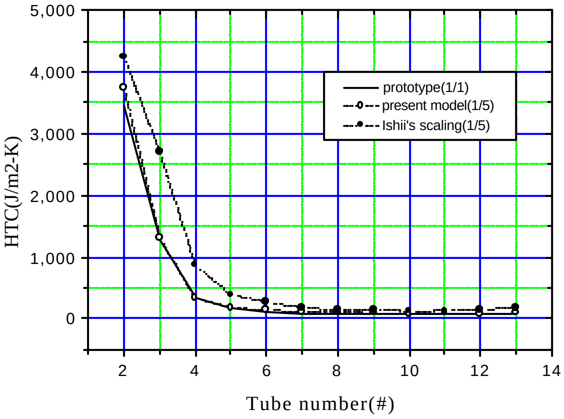

Fig. 13. Comparison of reflux condensation HTCs with non-condensable.