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Similarity Analysis for Reactor Flow Distribution Test and Its Validation

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1. Introduction

Scaling law for core flow distribution test was systematically derived from governing equations by Hong et al. in last Korean Nuclear Autumn Meeting 2014 held at Pyeongchang [1]. In this study Hetsroni's approach[2], which is based on Pi theorem and has been the technical basis of the most of the recent scaling analyses for the core flow tests[3], was intensively reviewed, and the role of gravity was discussed. And from the governing equations, instead of Pi theorem, important dimensionless groups were systematically obtained.

The newly derived dimensionless groups are slightly different from Hetsroni's. Reynolds number, relative wall roughness, and Euler don't appear, instead, friction factor appears newly. In order to conserve friction factor Reynolds number and relative wall roughness should be conserved. Since the effect of Reynolds number in high range is small, and since the scaled model is far smaller than prototype the conservation of friction factor is easily obtained by making the model wall just smooth. It is much easier to implement the test design than Hetsroni's because the Reynolds number and relative wall roughness do not appear explicitly.

In case that there is no free surface within the interested domain of the reactor, the gravity is of second importance, and in this case the pressure drops should be compensated for in order to compare them between prototype and model. The gravity head compensated pressure drop is directly same to the measured value by a differential pressure transmitter. In order to conserve the gravity effect Froude number should be conserved. In pool type SFR (Sodium Cooled Fast Reactor) there exists liquid level difference, and if the level difference is desired to be conserved, the Froude number should be conserved.

Euler number, which represents pressure terms in momentum equation, should be well conserved according to Hetsroni's approach. It is not a wrong statement, but it should be noted that Euler number is NOT an independent variable BUT a dependent variable according to Hong et al. It means that if all the geometrical similarity and the dimensionless numbers are conserved, Euler number is automatically conserved. So Euler number need not be considered in case that the perfect geometrical similarity is kept. However, even in case that the geometrical similarity is not conserved, it possible to conserved the velocity field similarity by just conserve Euler number. It gives tolerance to the engineer who designs the test facility. It was clearly found in Hong et al.

In this study the feasibility of the similarity analysis of Hong et al. was examined. The similarity analysis was applied to SFR which has been designed in KAERI (Korea Atomic Energy Research Institute)[4] in order to design the reactor flow distribution test. The length scale was assumed to be 1/5, and the velocity scale 1/2, which bounds the square root of the length scale ($1/\sqrt{5}$). The CFX[5] calculations for both prototype and model were carried out and the flow field was compared.

2. Summary of the Similarity Analysis of Hong et al.

The governing equations concerning reactor flow distribution test are continuity equation and momentum equation. From these two equations following dimensionless group are derived.

$$\textit{Froude number}: \qquad Fr = \frac{u^2}{g d_H} \quad (1)$$

$$\textit{Dimensionless Shear Stress Number}: \Pi_\tau = \frac{\tau_0}{\rho u_0^2} \quad (2)$$

Dimensionless shear stress number is reduced to friction number, and it is a function of Reynolds number and relative wall roughness.

$$\Pi_\tau = \frac{\tau_0}{\rho u_0^2} \sim f = fnc\left(Re, \varepsilon / d_H\right) \qquad (3)$$

If the pressure term in momentum equation is adjusted to include gravity term, Froude number is not derived explicitly. In this case the pressure should be compensated for by gravity head when comparing the prototypic pressure field and model pressure field. In other words the pressure is scaled by $p_R = \rho_R u_{0,R}^2$ but not by gravity head scale, i.e. $p_R \neq \rho_R l_{0,R}$. The subscript R means the ratio of model to prototype. If

Table I: Dimensionless groups and related constraints

Dimensionless Parameters	Expression by equation	Constraint	Remarks
Geometry	$\frac{l}{d_H}$	The same aspect ratio	Conservation of multi-dimensional phenomena
Froude number	$Fr = \frac{u_0^2}{gl_0}$	$u_{0,R} = \sqrt{l_{0,R}}$	Velocity scale is 1/2.24 in case of length scale 1/5. This value is similar to that of past test experiences, 1/2
Dimensionless shear stress number	$\Pi_\tau = \frac{\tau_0}{\rho u_0^2}$	$f_R = 1$	Implementation by the combination of Reynolds number and relative wall roughness
Euler number	$Eu = \frac{\Delta p}{\rho u_0^2 / 2}$	$\left(K + f\frac{L}{d_H} \right)_R = 1$	Geometry conservation or compensation of pressure drop by adjusting minor loss coefficient

Table II: Property ratio*

Water temperature (1 atm)	Density (kg/m^3)	Density ratio ($\rho_{0,R}$)	Viscosity (10^{-4}Ns/m^2)	Viscosity ratio ($\mu_{0,R}$)	Reynolds number ratio** ($Re_R = \rho_{0,R} u_{0,R} d_{H,R} / \mu_{0,R}$)
20℃	998.3	1/0.841 = 1.189	10.00	1/0.253 = 3.95	1/33.26 = 0.0301
40℃	992.3	1/0.846 = 1.182	6.53	1/0.387 = 2.58	1/21.85 = 0.0458
60℃	983.2	1/0.85 = 1.17	4.67	1/0.54 = 1.85	1/15.76 = 0.0635
80℃	971.7	1/0.86 =1.16	3.55	1/0.713 = 1.40	1/12.126 = 0.0825

* Sodium: 467.5℃ 1atm (core inlet temperature at normal operating condition)
density = 839.8 kg/m^3, Viscosity = 2.53X10^{-4} Ns/m^2
** Velocity scale: 1/2

Froude number is conserved in model, not only the pressure but also the head is scaled by $p_R = \rho_R u_{0,R}^2 = \rho_R l_{0,R}$.

In order to conserve the friction coefficient, which stands for the dimensionless shear stress number, Reynolds number and relative wall roughness should be conserved. But since the effect of Reynolds number becomes smaller as it becomes larger, the more important is relative wall roughness. Thus, in 1/5 length scaled model the wall should be nearly smooth.

Pressure term in momentum equation is transformed to Euler number, so Euler number is not an independent variable but a dependent variable. Euler number is expressed as follow;

$$Euler\ Number: Eu = p^* = \frac{p}{\rho u_0^2 / 2} \sim \frac{\Delta p}{\rho u_0^2 / 2} \quad (4)$$

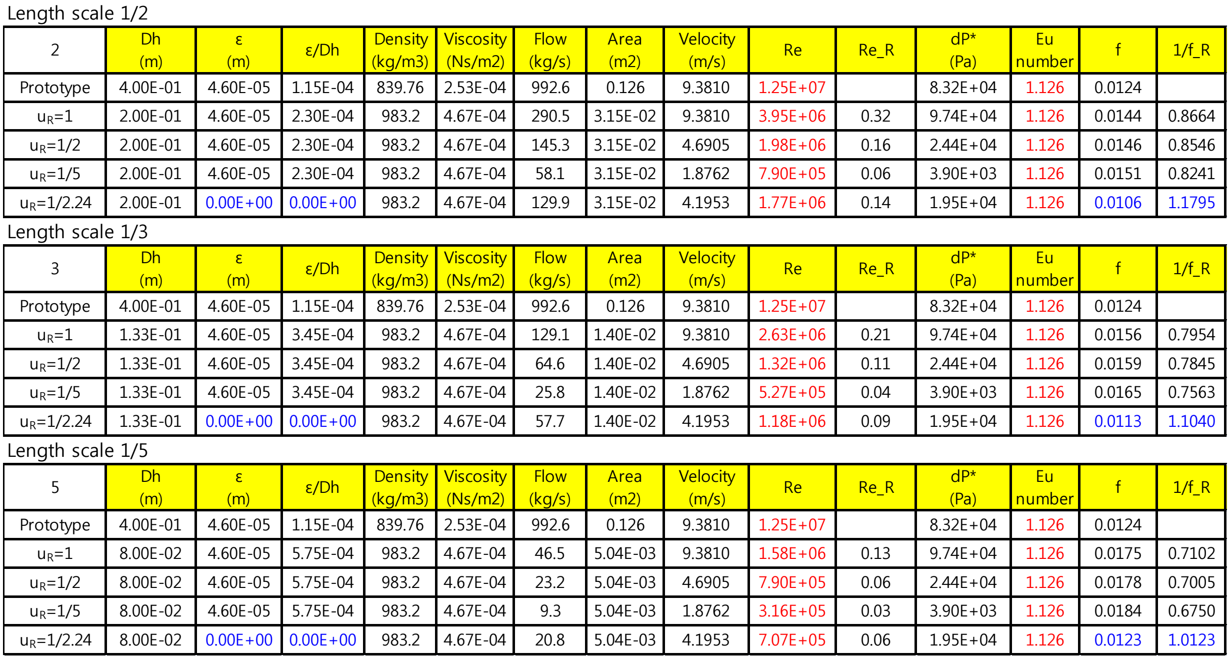
Thus, if all the coefficients such as Froude number and source terms such as dimensionless shear stress number in the dimensionless momentum equation are same each other in prototype and model, the dimensionless continuity equation and dimensionless momentum equations surely yield the same dimensionless velocity and dimensionless pressure (it is Euler number) when the geometrical similarity is maintained. It means that Euler number is automatically conserved. However, even in case that the geometrical similarity is not conserved in some location, the same dimensionless velocity can be easily obtained in the locations which are far from the distorted geometry, as

Table III: Dynamics scales

Parameter		Scaling variable	Scale	Remarks
Flow velocity		$u_{0,R}$	1/2	This velocity scale bounds $u_{0,R} = \sqrt{l_{0,R}} \simeq 1/2.24$
Flow		$\dot{m}_R = \rho_R u_{0,R} l_{0,R}^2$	1/42.7	-
Friction factor related variables (at pump outlet)	Relative wall roughness	$\left(\dfrac{\varepsilon}{d_H}\right)_R$	1/1	If this parameter is approximately conserved, a similar friction factor in model can be obtained in spite that Reynolds number is not fully conserved.
	Re number	$Re_R = \dfrac{\rho_R u_{0,R} d_{H,R}}{\mu_R}$	1/15.77	$u_{0,R} = \sqrt{l_{0,R}} \simeq 1/2.24$ instead of 1/2 yields Re_R = 1/17.63. But the friction facto is rarely affected.
	Friction factor*	$f_R = \dfrac{f_m(\varepsilon/d_H, Re)}{f_p(\varepsilon/d_H, Re)}$	1/0.7006	Same wall roughness
			1/0.9022	Same relative wall roughness
			1/1.0323	Smooth wall in model
Pressure drop		$\Delta p_R = \rho_{0,R} u_{0,R}^2$	1/3.42	In case that friction factor is not perfectly conserved, minor loss coefficient (K) is to be adjusted in order to conserve the pressure drop ratio.

* If the model wall is made smooth, friction factor is approximately conserved in model.

Table IV: Check of the friction factor at pump discharge pipe



Length scale 1/2

2	Dh (m)	ε (m)	ε/Dh	Density (kg/m3)	Viscosity (Ns/m2)	Flow (kg/s)	Area (m2)	Velocity (m/s)	Re	Re_R	dP* (Pa)	Eu number	f	1/f_R
Prototype	4.00E-01	4.60E-05	1.15E-04	839.76	2.53E-04	992.6	0.126	9.3810	1.25E+07		8.32E+04	1.126	0.0124	
u_R=1	2.00E-01	4.60E-05	2.30E-04	983.2	4.67E-04	290.5	3.15E-02	9.3810	3.95E+06	0.32	9.74E+04	1.126	0.0144	0.8664
u_R=1/2	2.00E-01	4.60E-05	2.30E-04	983.2	4.67E-04	145.3	3.15E-02	4.6905	1.98E+06	0.16	2.44E+04	1.126	0.0146	0.8546
u_R=1/5	2.00E-01	4.60E-05	2.30E-04	983.2	4.67E-04	58.1	3.15E-02	1.8762	7.90E+05	0.06	3.90E+03	1.126	0.0151	0.8241
u_R=1/2.24	2.00E-01	0.00E+00	0.00E+00	983.2	4.67E-04	129.9	3.15E-02	4.1953	1.77E+06	0.14	1.95E+04	1.126	0.0106	1.1795

Length scale 1/3

3	Dh (m)	ε (m)	ε/Dh	Density (kg/m3)	Viscosity (Ns/m2)	Flow (kg/s)	Area (m2)	Velocity (m/s)	Re	Re_R	dP* (Pa)	Eu number	f	1/f_R
Prototype	4.00E-01	4.60E-05	1.15E-04	839.76	2.53E-04	992.6	0.126	9.3810	1.25E+07		8.32E+04	1.126	0.0124	
u_R=1	1.33E-01	4.60E-05	3.45E-04	983.2	4.67E-04	129.1	1.40E-02	9.3810	2.63E+06	0.21	9.74E+04	1.126	0.0156	0.7954
u_R=1/2	1.33E-01	4.60E-05	3.45E-04	983.2	4.67E-04	64.6	1.40E-02	4.6905	1.32E+06	0.11	2.44E+04	1.126	0.0159	0.7845
u_R=1/5	1.33E-01	4.60E-05	3.45E-04	983.2	4.67E-04	25.8	1.40E-02	1.8762	5.27E+05	0.04	3.90E+03	1.126	0.0165	0.7563
u_R=1/2.24	1.33E-01	0.00E+00	0.00E+00	983.2	4.67E-04	57.7	1.40E-02	4.1953	1.18E+06	0.09	1.95E+04	1.126	0.0113	1.1040

Length scale 1/5

5	Dh (m)	ε (m)	ε/Dh	Density (kg/m3)	Viscosity (Ns/m2)	Flow (kg/s)	Area (m2)	Velocity (m/s)	Re	Re_R	dP* (Pa)	Eu number	f	1/f_R
Prototype	4.00E-01	4.60E-05	1.15E-04	839.76	2.53E-04	992.6	0.126	9.3810	1.25E+07		8.32E+04	1.126	0.0124	
u_R=1	8.00E-02	4.60E-05	5.75E-04	983.2	4.67E-04	46.5	5.04E-03	9.3810	1.58E+06	0.13	9.74E+04	1.126	0.0175	0.7102
u_R=1/2	8.00E-02	4.60E-05	5.75E-04	983.2	4.67E-04	23.2	5.04E-03	4.6905	7.90E+05	0.06	2.44E+04	1.126	0.0178	0.7005
u_R=1/5	8.00E-02	4.60E-05	5.75E-04	983.2	4.67E-04	9.3	5.04E-03	1.8762	3.16E+05	0.03	3.90E+03	1.126	0.0184	0.6750
u_R=1/2.24	8.00E-02	0.00E+00	0.00E+00	983.2	4.67E-04	20.8	5.04E-03	4.1953	7.07E+05	0.06	1.95E+04	1.126	0.0123	1.0123

* dP: Pressure drop
Water in model is 60℃

long as the Euler number is conserved. Euler number gives much tolerance to the test designer.

3. Scaling Ratio and Design Parameters

3.1 Overall design

The working fluid in the prototypic SFR is sodium, but the sodium is changed into water in the model facility for the safety and convenience in experiment.

Table V: Model geometry design

Geometry	Prototypic SFR (mm)	1/5 model (mm)
Reactor vessel I.D.	8554	1711
Reactor vessel Height	15444	30898
Core Height	4220	844
Core Shroud I.D	2808	562
Lower core Shield I.D	3294	659
Inlet Plenum Height	800	160
Inlet Plenum Nozzle Dia.	305	61
Pump Discharge Pipe Dia.	400	80
DHX Outlet Height	254	51
IHX I.D	1302	260
IHX flow path length	6025	1205
IHX Inlet Window Width(rΘ)	250	50
IHX Inlet Window Height	610	122
IHX Outlet Dia.	630	126
DHX I.D	418	84
DHX flow path length	1730	346
DHX Inlet Window Width(rΘ)	124	25
DHX Inlet Window Height	254	51

The summarized conserved parameters are shown in Table I together with the constraints in test facility design.

Property scale by sodium-to-water scaling is summarized in Table II. The density and viscosity of water are larger than those of sodium. And as the water temperature increases, Reynolds number less decreases. Thus high temperature water is better than cold water. Test water was decided as 60℃ considering test cost and safety.

For these conditions and scales the dynamics scale are calculated as Table III. Table IV shows the friction factor trends in model at various length scale and velocity scale. With length scale 1/5 and velocity scale 1/2, large model Reynolds number can be obtained sufficient to make the model fully turbulent. It means such length and velocity scales are justified for the reactor flow test.

Some important model geometry is presented in Table V. All the design values are acceptable for the manufacturing.

3.2 Components design

For the circulation of coolant the model pump was designed to be located in reactor outside. The inlet and outlet parts of the prototypic pump were designed to have the same coaxial annulus pipe. The prototypic motor parts were utilized as transmission coaxial annulus pipe. Above the model reactor outside the coaxial annulus pipe is divided into normal pipes.

Model IHX (Intermediate Heat eXchanger) was designed to have the shape of venturi tube to measure the flowrate. In spite of the geometry distortion it was carefully designed to have the scaled pressure drop. DHX (Decay Heat eXchanger) has so small pressure drop to be accounted for it was neglected by blocking the inlets and outlets.

Fuel assemblies were designed to have venturi tube and orifices. Of course the pressure drop across the fuel assembly has the scaled value. Fuel assembly groups 11 and 12 are blocked because of their so small flowrate.

All the component designs were check by CFX calculations.

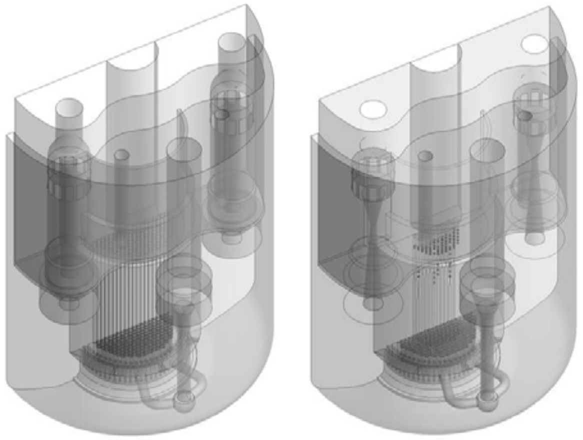


Fig. 1. Geometric model of the prototype(left) and the model(right)

Table VI: Flow validation

Fuel assembly group	Prototype flow rate by CFD (A)[kg/s]	Model flow rate by CFD (B=A* $\dot{m}_R$)[kg/s]	Required model value (C) [kg/s]	Error (D=(B-C)/C)
1	23.45	0.573	0.55	0.043
2	22.21	0.527	0.52	0.014
3	21.20	0.506	0.50	0.019
4	19.44	0.460	0.46	0.011
5	16.24	0.377	0.38	-0.008
6	15.58	0.372	0.36	0.020
7	14.25	0.331	0.33	-0.008
8	12.70	0.295	0.30	-0.007
9	11.32	0.256	0.27	-0.033
10	0.4781	0.0116	0.0112	0.036
11	0.1784	-	0.0042	-
12	0.0251	-	0.0006	-

Table VII: Pressure drop validation

Location	Prototype pressure drop by CFD (A) [kPa]	Model pressure drop by CFD (B=A*p_R) [kPa]	Required model value (C) [kPa]	Error (D=(B-C)/C)
Core	442	131.7	129.24	0.019
IHX	26.9	7.3	7.87	-0.072
Pump	84	21.4	24.6	-0.129
Inlet plenum	35.6	10.8	10.4	0.038
Pump discharge pipe	90.5	28.8	26.5	-0.088
Total	679	200	198.53	0.007

4. Validation of the Scaling Analysis

In order to validate the scaling analysis discussed above, CFX calculation for both prototype and model were carried out, and the flow velocities (or flowrates) and pressure drops were compared.

4.1 CFX modeling

Geometric models of the prototype and the model are shown in Fig.1. A three-dimensional (3D) grid was generated, covering only one half of the vessel. This was possible due to the assumption of symmetry relative to the vertical plane crossing the core region. The numerical grid consists of elements of 68,384,158 for the prototype and elements of 126,173,061 for the model, respectively. The following options were prescribed in the input models for the CFX code:

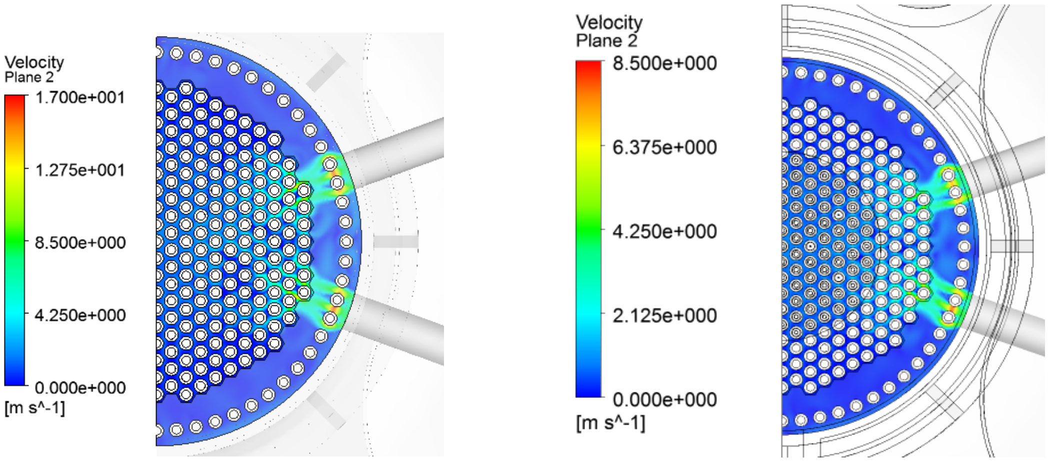
- Turbulent flow (standard k- ε model).
- No-slip condition at the vessel walls and on vessel internal structures for the model.
- Rough-wall condition at the vessel walls and on vessel internal structures for prototype, and smooth wall for model.

In order to simulate the hydraulic resistance in prototype some regions such as the fuel assembly, IHX and UIS were modeled as a porous. In case of the fuel assembly, the loss coefficients were calculated for each flow group.

4.2Validation of scaling analysis

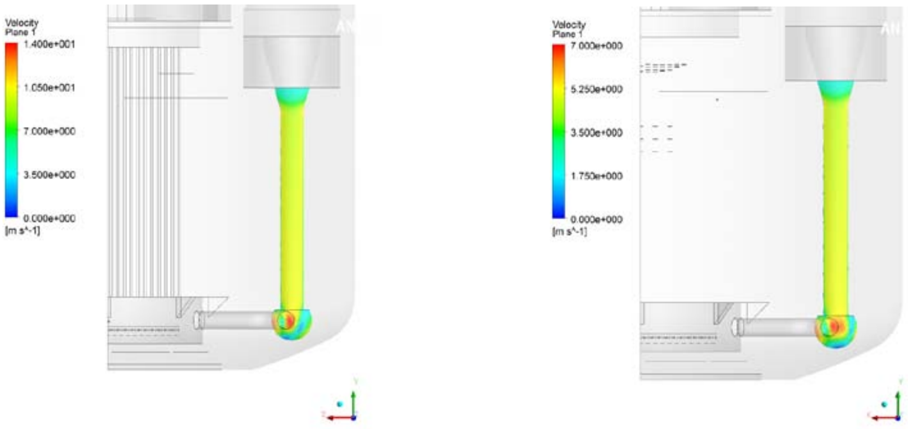
Scale downed model flowrates which are derived from prototypic CFX calculation are compared to the model CFX calculations in Table VI. It shows very similar flowrates. Pressure drop comparisons are presented in Table VII for important location and total pressure drop. It also shows good agreement.

Flow field comparisons are presented in Figs. 2 to 4. They also show similar flow field with just a slight



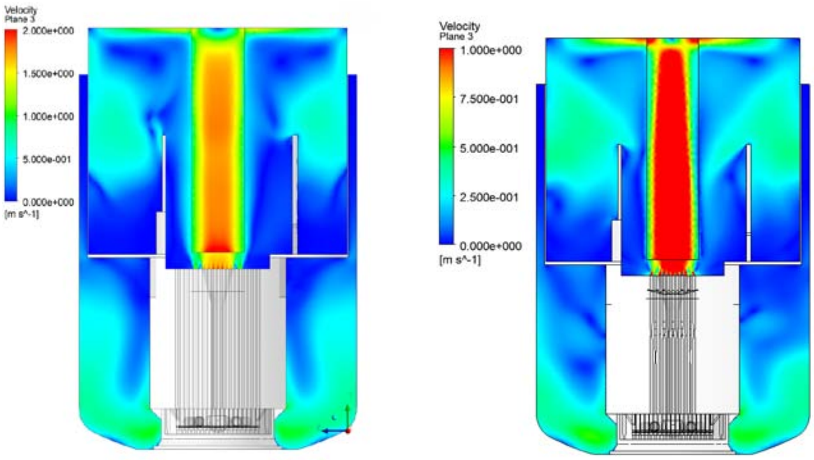
(a) prototype (b) model

Fig. 2. Flow field comparison for inlet plenum



(a) prototype (b) model

Fig. 3. Flow field comparison for pump discharge pipe



(a) prototype (b) model

Fig. 4. Flow field comparison for reactor pool

distortions. It may be caused by the distorted jet penetration.

5. Conclusions

This paper presents the design parameters according to the scaling analysis of Hong et al., and its validation using CFX calculation. The test model is designed to have length scale 1/5 and velocity scale 1/2. And the model uses 60℃ water instead of sodium. The CFX results of both prototype and model shows appropriate similarities in flow and pressure drop. Flow field also showed a relatively good agreement between prototype and model but slight difference was revealed. It may be resulted in by the distortion of jet penetration, which should be investigated in further study.

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