Reactor Flow and Structure Vibration Models

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1. Introduction

The test facility in which a 1/5 scale model to simulate the advanced power reactor, to investigate both the flow mixing and Flow Induced Vibration (FIV), has been constructed. The scale model has instrumented both for the flow mixing and the pressure perturbation measurements as well as structure vibration measurements. The overall goal of the scale model tests is to set up the scaling method and instrumentation skills for FIV test such as Comprehensive Vibration Assessment Program (CVAP) scaled model tests. The data on the turbulence-induced pressure perturbation in functions of Power Spectral Density (PSD) needs to determine the vibration level by the excitation pressure perturbation onto an internal structure such as the core barrel inside a reactor vessel. Work by Au Yang, and more recent work, has shown that model test PSD correlations are not an accurate predictor of turbulence PSDs in the full-scale plant [2.3]. Work by Snyder et al. [4,5] has shown, for instance, that turbulence flow vorticity may be a useful parameter and could leader to the development of more accurate PSD correlations. Further investigation of the utility of vorticity is recommended.

2. SCALING

2.1 Flow Mixing Scaling

For a steady-state single phase flow without free surface, the following dimensionless Navier-Stocks equation is simplified expressed as

$$(u^* \cdot \nabla^*)u = -\nabla^* p^* + \frac{1}{Re}\nabla^{*2}u^* \qquad (1)$$

where,

$$p^* = Eu = \frac{P}{\rho u_o^2} \sim \frac{dP}{\rho u_o^2}$$

$$Re = \frac{\rho u_o L}{\mu}$$

$$\Delta P = f\left(Re, \frac{\epsilon}{D}\right)\frac{L}{D}\frac{\rho u^2}{2}$$

The velocity scale is preserved by the Euler (Eu) number for the scaled model. The relationship between the reduced velocity scale and the length scale is obtained as follows:

$$u_{oR} = \sqrt{L_R}$$

To preserve the flow rate distribution in a scaled reactor model, the L/D aspect ratio of should be held to 1.

$$Aspect\ ratio = \left({L}/{D}\right)_R = 1$$

Table 1 Scaling parameters of the 1/5-scale model [1]

Parameter	Proto	1/5 Model	Ratio
Length	L_{Ref}	1/5	l_R
Area	A_{Ref}	1/25	l^2_R
Aspect Ratio	$(L/D)_{Ref}$	1	*1*
Velocity	V_R	R /SQRT(5)	$1^{1/2}{}_R$
Density	*REF*	1.3	*R*
Viscosity	*REF*	5.26	*R*

2.2 Structure Vibration Scaling

For the structure vibration, the following equation is simplified expressed as

$$f = \frac{1}{2\pi} \cdot \sqrt{\frac{k}{m}} \qquad (2)$$

The metal frequency ratio between the prototype and the scaled model becomes

$$f_R = \frac{\left(\frac{1}{2\pi}\sqrt{\frac{k}{m}}\right)_m}{\left(\frac{1}{2\pi}\sqrt{\frac{k}{m}}\right)_p} = \sqrt{\frac{k_m}{k_p}\frac{m_p}{m_m}} = \sqrt{\frac{E_R \cdot l_R}{l_R^3 \cdot \rho_R}} = \frac{1}{l_R}\sqrt{\frac{E_R}{\rho_R}}$$

where,

$$E_R = \frac{E_m}{E_p}, \rho_R = \frac{\rho_m}{\rho_p}, k = \frac{AE}{L}$$

If, $E_R = 1$, and $\rho_R = 1$

The metal frequency ratio becomes

$$f_R = \frac{1}{l_R}$$

2.3 Turbulence Pressure Perturbation Scaling

The Euler number to be an approximate function of the reduced frequency, thus

$$Eu = \frac{p}{\rho_f V^2} = F\left(\frac{f\delta}{V}\right) \quad (3)$$

The normalized PSD was defined as

$$\bar{\Phi}_p(\bar{f}) = \frac{G_p(f)}{4\left(\frac{\rho_f V^2}{2}\right)^2\left(\frac{\delta}{V}\right)}; \quad \bar{f} = \frac{f\delta}{V} \quad (4)$$

This leads to the following similarity relation between model (M) and prototype (P):

$$\begin{aligned} \bar{\Phi}_p(\bar{f})_P &= \bar{\Phi}_p(\bar{f})_M \\ G_p(f)_P &= G_p(f)_M \cdot \frac{V_P^3}{V_M^3} \\ \bar{f}_P &= \bar{f}_M \\ \left.\frac{f\delta}{V}\right|_P &= \left.\frac{f\delta}{V}\right|_M \end{aligned} \quad (5)$$

The *rms* turbulence pressure can be obtained from the pressure PSD via the integral:

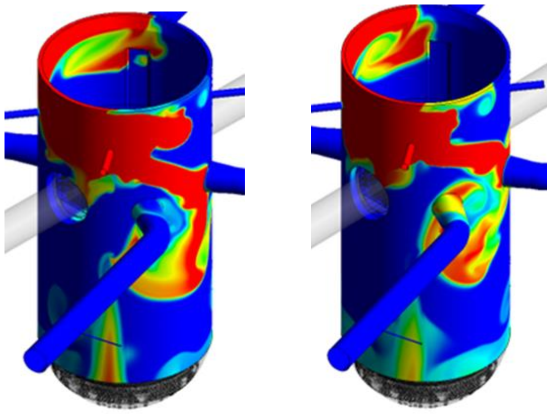
$$\begin{aligned} \overline{p^2} &= \int G(f)df \\ &\approx \int \rho_f^2 V^3 \delta . \bar{\Phi}_p(\bar{f}).d\left(\frac{\bar{f}V}{\delta}\right) \end{aligned} \quad (6)$$

The Eu scaling above may not fully capture the relation between model and prototype turbulence pressures. Frequency effects, for example, may cause distortion of the Eu scaling. At the same time, such distortion may provide information on differences in turbulence generation and excitation mechanisms between model and prototype. The Kolmogorov cascade power law may be valid in the reactor downcomer Sugiura et al. [6]

3. Results

3.1 Mean Flow Similarity

Fig. 1 shows the downcomer flow distribution that simulated by CFX code. As shown in the figure, the flow distribution of scaled model had a very similar contour and patterns compared to those of the prototype. The borated water injected into the reactor vessel through a DVI nozzle was not mixed evenly over the core and downcomer section.



(a) Prototype(Full scale) (b)1/5-scale model
Fig.1 Flow distribution in the downcomer

3.2 Structure Vibration Similarity

Table 2 summarized the natural frequency of the full scale model and the 1/5 scale model. The frequency of the scaled model is amplified by 5 times when compared those of the full scale model because the length scale is 1/5. Fig.2 show the vibration mode shapes of the core barrel.

Table 2 Modal frequency

Mode (circumf., axial)		1/5 model (a)	Proto (b)	Ratio (a)/(b)
1	(2, 0)	61.0	12.2	5.00
2		62.0	12.4	5.00
3	(2, 1)	94.2	18.8	5.00
4		94.6	18.9	5.00
5	(3, 0)	162.1	32.4	5.00
6		165.5	33.1	5.00
7	(3, 1)	225.1	45.0	5.00
8		228.4	45.7	5.00
9	(2, 2)	284.5	56.9	5.00
10		290.2	58.0	5.00

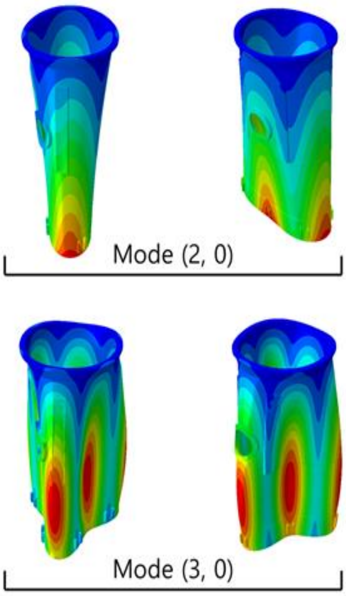


Fig.2 Mode shapes of vibration.

4. Conclusions

The CFD analysis performed to evaluate the mixing similarity of the downcomer and core driven by the CVCS and SCS for prototype and 1/5-scale models. For the CVCS and SCS pump running forced flow conditions, the flow distributions in the reactor core and the downcomer were well preserved for the 1/5-linear scaled model. The borated water injected through the DVI nozzle (for the SCS) and the cold leg (for the CVCS) was not mixed evenly over the core section. However, the flow patterns of the core zone with a free cavity and mixing vane models were well preserved between the prototype and 1/5-Scale models.

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