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# Study on the Scaling of Core Flow Distribution Test

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## 1. Introduction

Safety of nuclear power plant is assured through the safety and performance analyses for the reactor, and they are largely dependent on the core inlet flow distribution. Of course, when evaluating the core thermal margin, the flow distribution in reactor is also very important. Thus, the identification of reactor hydraulic characteristics is essential process in the nuclear reactor design. Actually several core flow distribution tests were carried out with small scaled models. It is known that ABB-CE conducted the test for the design of System 80 reactor using a 3/16 scaled model reactor in the last 1970s. In domestic industry experimental studies was carried out in 1990s using a 1/5.03 scale reactor flow model of Yong-gwang nuclear units 3 and 4. Euh et al. studied the core flow distribution tests with 1/5 scaled test facilities for SMART and APR+ in 2000s, respectively [1].

Theoritical basis for such tests are on Hetsroni's study [2]. In this study he proposed seven important parameters which largely affect the hydraulics of the core flow distributions. Through the non-dimensionalization process using Pi theorem, he suggested four principal dimensionless groups; geometrical constrain (aspect ratio), relative wall roughness, Reynolds number, and Euler number.

This paper studies the scaling of core flow distribution for a pool type sodium fast reactor (SFR). At first Hetsroni's study was intensively reviewed, and a general derivation of the dimensionless groups from the governing equations is presented. Finally, the applicability of the derived approach is tested for a pool type SFR.

## 2. Review of Hetstroni's Approach

Hetsroni identified the 7 important parameters which are inter-related with each other in the core flow distribution;

$$p = \psi\left(u, \rho, \nu, L, D_H, \varepsilon\right) \qquad (1)$$

, where $p$, $u$, $\rho$ , $\nu$, $L$ $D_H$, and $\varepsilon$ are pressure, velocity, density, kinematic viscosity, hydraulic diameter, and wall roughness, respectively. This can be reduced to four dimensionless groups with the help of Pi Theorem.

$$\frac{\Delta p}{\rho u^2/2} = \psi^*\left(\frac{L}{D_H}, \frac{\varepsilon}{D_H}, \frac{uD_H}{\nu}\right) \qquad (2)$$

, where the left hand side is Euler number, and the right hand side are aspect ratio, relative wall roughness, and Reynolds number, respectively.

According to Hetsroni the similarity in geometry, which is corresponding to the aspect ratio and the relative wall roughness, was decided to be maintained between prototype and model wherever possible. And it was concluded that Euler number should be similar in both the prototype and the model. However, Reynolds number is less important in high turbulent region, because form loss coefficient is independent of Reynolds number and friction factor is just weakly dependent on Reynolds number.

A modern sophisticated expression for the similarity requirement is given by

$$\psi_R \equiv \frac{\psi_m}{\psi_p} = 1 \qquad (3)$$

, where $\psi$ is a dimensionless group, and subscripts m, p, and R indicate model, prototype, and model-to-prototype ratio, respectively. This relation means that the model dimensionless group should be same to prototypic dimensionless group.

Reconsidering Eq. (2) on the base of the requirement given by Eq. (3), following insights can be obtained:

(1) From the conservation of aspect ratio number, the length scale and diameter scale are independent, i.e., different scale can be set. However, it is out of general consensus for the geometry constrains in multidimensional phenomena. When deriving dimensionless groups from the multidimensional governing equation, the same length scale in all coordinates are inevitable [3.4]. Actually, Hetsroni also used the same length scale in diameter and longitude.
(2) Similarity criterion also requires the relative wall roughness to be conserved. That is, in a small scaled model the model wall roughness should be reduced by the factor of the diameter scale. It is surely a very tiresome request.

(3) Less importance of Reynolds number is not explicitly shown in Eq. (2). In other words, the relation between Reynolds number and friction coefficient is not revealed at least in Eq. (2). It seems that Eq. (2) requires Reynolds number to be conserved. More logical explanation is desired for the clear understanding of the less importance of Reynolds number.

(4) Generally speaking, a pressure drop is composed of frictional pressure drop including minor loss pressure drop caused by a change of flow path form to the comprehensive extent, gravitational pressure drop, and acceleration pressure drop. In steady-state single-phase liquid flow the acceleration pressure drop is usually small sufficient to be neglected. However, the gravitational pressure drop is another problem. It can be an important contribution. However, Hetsroni did not consider the effect of gravitation at least in explicit manners.

(5) There is a no constrain in velocity scale. Arbitrary velocity scale is allowed. Is it right indeed?

From the discussions above, it can be concluded that more elaborate derivation for the similarity is highly desired.

## 3. Consideration of Gravity

The Hetsroni's identification and be modified into following equation on the consideration of gravity;

$$p = \psi\left(g, u, \rho, \nu, L, D_H, \varepsilon\right) \quad (4)$$

Using the Pi Theorem dimensionless groups can be obtained.

$$\frac{p}{\rho u^2/2} = \psi^*\left(\frac{L}{D_H}, \frac{\varepsilon}{D_H}, \frac{uD_H}{\nu}, \frac{u^2}{gD_H}\right) \quad (5)$$

Last term in the parenthesis in right hand side of Eq. (5) appears newly. This is Froude number. In order to conserve Froude number the velocity scale should be a square root of length scale (or diameter scale). It is different from Hetsroni's.

Here, another try can be conducted. That is, when compensating for the gravity effect in pressure term, following relation can be setup.

$$\begin{aligned} & p - p_{grav} = \psi\left(u, \rho, \nu, L, D_H, \varepsilon\right) \\ & , where\ p_{grav} = \rho g z \sin\theta \sim \rho g L \end{aligned} \quad (6)$$

And this equation can be transformed into dimensionless form;

$$\frac{\Delta\left(p - p_{grav}\right)}{\rho u^2/2} = \psi^*\left(\frac{L}{D_H}, \frac{\varepsilon}{D_H}, \frac{uD_H}{\nu}\right) \quad (7)$$

This is the same result with Hetsroni. It means that the gravity effect in pressure should be compensated for when analyzing the core flow distribution on the base of Hetsroni's. Velocity constrain is also untied.

## 4. Derivation of Dimensionless Groups

### *4.1 Derivation from general governing equation*

Single phase continuity equation does not produce any dimensionless group, and it need not be considered. Steady-state momentum equation is given by

$$\left(\mathbf{u}\cdot\nabla\right)\left(\rho\mathbf{u}\right) = -\nabla p + \rho\mathbf{g} + \nabla\cdot\boldsymbol{\tau}_{ij} \quad (8)$$

$$\mathbf{T} = \boldsymbol{\tau} - p\mathbf{I} + {}_{ij} \quad (9)$$

, where bold $\mathbf{u}$, $\mathbf{g}$, $\boldsymbol{\tau}_{ij}$, $\mathbf{T}$, and $\mathbf{I}$ are velocity vector, gravity vector, shear stress tensor, stress tensor, and unit tensor, respectively. In order to nondimensionalize Eq. (8) following nondimensionalizing parameters are introduced.

$$\begin{aligned} & \nabla^* = L\nabla, \quad \mathbf{u}^* = \frac{\mathbf{u}}{u_0}, \\ & p^* = \frac{p}{\rho u_0^2/2}, \quad \boldsymbol{\tau}_{ij}^* = \frac{\boldsymbol{\tau}_{ij}}{\tau_0} \end{aligned} \quad (10)$$

, where subscript 0 means a reference point value. Dimensionless momentum equation has following form;

$$\left(\mathbf{u}^*\cdot\nabla^*\right)\mathbf{u}^* = -\nabla^* p^* + \frac{1}{Fr}\hat{\mathbf{g}} + \Pi_\tau \nabla^*\cdot\boldsymbol{\tau}_{ij}^* \quad (11)$$

, where $\hat{\mathbf{g}}$ is dimensionless gravity unit vector. And there are several dimensionless groups;

$$\begin{aligned} & Eu = p^* = \frac{p}{\rho u_0^2/2} \sim \frac{\Delta p}{\rho u_0^2/2}, \\ & Fr = \frac{u_0^2}{gL}, \\ & \Pi_\tau = \frac{\tau_0}{\rho u_0^2} \end{aligned} \quad (12)$$

### *4.2 Dimensionless shear stress number*

For the dimensionless shear stress number, shown in the last row in eq. (12) following simple relation can be considered.

$$\tau = -\mu\frac{du_p}{dy} \quad (13)$$

, where $\mu$ , $u_p$, and $y$ are viscosity, velocity parallel to wall surface, and coordinate perpendicular to the wall surface, respectively. And the dimensionless shear stress number can be further developed

$$\Pi_\tau = \frac{\tau_0}{\rho u_0^2} = -\frac{1}{Re}\frac{d^* u_p^*}{dy^*} \quad (14)$$

Here two new dimensionless groups are drived.

Reynolds number $Re = \frac{\rho u_0 L}{\mu_0}$ (15)

Dimensionless wall velocity gradient number

$$\Pi_{v\_grad} = \frac{d^* u_p^*}{dy^*} \sim \frac{u_p / u_0}{D_H / L} \quad (16)$$

For the similarity the dimensionless wall velocity gradient number should be conserved, and $u_p$ should have the same scale with reference velocity $u_0$. In order to check this requirement a near wall velocity profile is to be reviewed, which is usually given by following wall function.

$$u^+ \equiv \frac{u_p}{u^\#} = \frac{yu^\#}{\nu} \equiv y^+ \quad (17)$$

, where u# means shear velocity. Therefore, the variation of $u_p$ along with $y$ direction can be calculated.

$$u_p(y) = \frac{y(u^\#)^2}{\nu} = \frac{y}{\nu}\left(\frac{\tau_w}{\rho}\right) \sim \frac{y}{\mu}\left(C_f \frac{1}{2}\rho u_0^2\right) \sim \frac{D_H}{\mu}\left(f \frac{1}{2}\rho u_0^2\right) \quad (18)$$

, where $C_f$ is fanning friction factor, and $f$ is Darcy-Weisbach friction factor, which is four times of fanning friction factor. In order to scale $u_p$ by the reference velocity scale the friction factor can be adjusted by controlling wall roughness or flow diameter, and so on. Moreover, in order to conserve the dimensionless shear stress number under the condition of distorted Reynolds number in Eqs. (14) and (15) the friction factor also can be adjusted. Here it should be noticed that the Reynolds number tends to be saturated at high value. Thus, the relative wall roughness alone remains the key factor to determine friction factor.

### *4.3 Euler number*

Pressure drop by friction can be extended to minor loss.

$$\Delta p \sim \left(K + f\frac{L}{D_H}\right)\frac{1}{2}\rho u_0^2 \quad (19)$$

Thus, for the conservation of Euler number the pressure drop by summing both friction and minor loss should have the following relation;

$$Eu = \frac{\Delta p}{\rho u_0^2 / 2} \sim \left(K + f\frac{L}{D_H}\right) \quad (20)$$

, where K is minor loss coefficient. This means the sum of both minor loss coefficient and friction loss coefficient should be adjusted. This is easier handling method compared to handling each independently. By adjusting K easier conservation is possible. But care should be taken in that the flow path shape should be modified at a spot which does not affect much the flow field. Here K includes the effect of flow path shape change, entrance effect, the effect of turbulent, and so on.

### *4.4 Froude number*

The similarity requirement of Froude number constrains the velocity scale to be a square root of length scale.

### *4.5 Geometry constrain.*

As shown in the first term in Eq. (10) the aspect ratio should be same. This is newly revealed in this derivation, whereas Hetsroni did not explicitly point out.

Table I: Geometry scale and property scale

| | 1/5 Linear Scaled Model | | |
|---|---|---|---|
| | Scale | Value | Remarks |
| Length | $l_R$ | 1/5 | |
| Height | $l_R$ | 1/5 | |
| Diameter | $l_R$ | 1/5 | |
| Flow Area | $l_R^2$ | 1/25 | |
| Density | $\rho_R$ | 1/0.855 | Atmospheric 60℃ Water vs. atmospheric 467.5℃ sodium |
| Viscosity | $\mu_R$ | 1/0.543 | |

Table II: Geometry design

| $l_R$ =1/5 | SFR(mm) | Model (mm) |
|---|---|---|
| Reactor vessel I.D. | 8554 | 1710.8 |
| Reactor vessel Height | 15444 | 3088.78 |
| Core Height | 4220 | 844 |
| Core Shroud I.D | 2808 | 561.6 |
| Lower core Shield I.D | 3294 | 658.8 |
| Inlet Plenum Height | 800 | 160 |
| Inlet Plenum Nozzle Dia. | 305.2 | 61.04 |
| Pump Discharge Pipe Dia. | 400 | 80 |
| DHX Outlet Height | 254 | 50.8 |

## 4. Scaling Factors for the Design of Model

In order to check the applicability of the above theory, sample calculation was carried out for pool type SFR design in KAERI. The model is scale by 1/5, and uses water instead of sodium.

Table III: Flow and pressure drop scale according to velocity scale

| Linear Scaling Method | Scale | Ideal Value | |
|---|---|---|---|
| Velocity scale (1) | $u_R$ | 1 | Conserve velocity |
| Flowrate | $(\rho_R)(u_R)(A_R)$ | 1/21 | |
| Re | $(\rho_R)(u_R)(L_R)/(\mu_R)$ | 1/7.7 | |
| Press. drop | $(\rho_R)(u_R)^2$ | 1/0.86 | |
| | | | |
| Velocity scale (2) | $u_R$ | 1/2 | APR+ case |
| Flowrate | $(\rho_R)(u_R)(A_R)$ | 1/42.7 | |
| Re | $(\rho_R)(u_R)(L_R)/(\mu_R)$ | 1/15.7 | |
| Press. drop | $(\rho_R)(u_R)^2$ | 1/3.4 | |
| | | | |
| Velocity scale (3) | $u_R$ | 1/5 | Same time scale |
| Flowrate | $(\rho_R)(u_R)(A_R)$ | 1/106.8 | |
| Re | $(\rho_R)(u_R)(L_R)/(\mu_R)$ | 1/39.3 | |
| Press. drop | $(\rho_R)(u_R)^2$ | 1/21.4 | |
| | | | |
| Velocity scale (4) | $u_R$ | | Conserve Fr |
| Flowrate | $(\rho_R)(u_R)(A_R)$ | 1/47.9 | |
| Re | $(\rho_R)(u_R)(L_R)/(\mu_R)$ | 1/17.6 | |
| Press. drop | $(\rho_R)(u_R)^2$ | 1/4.27 | |

Table I is the important scale factors. Based on this table, Table II was obtained for various locations. Table III is the flow and pressure drop scale for various velocity scales. Obtained model dimensions are acceptable sizes. Table IV is the Reynolds number in models according to velocity scale. All model Reynolds number are sufficiently large.

Table IV: Scale of Reynolds number

| | Flow (kg/s) | Velocity (m/s) | Re | Re(p) /Re(m) |
|---|---|---|---|---|
| Prototype | 496.3 | 8.074 | 8.18E+08 | |
| Model velocity (1/1) | 23.24 | 8.074 | 1.04E+06 | 7.87 |
| Model velocity (1/2) | 11.62 | 4.04 | 5.20E+05 | 15.74 |
| Model velocity (1/5) | 4.65 | 1.62 | 2.08E+05 | 39.24 |
| Model velocity (1/2.24) | 10.37 | 3.60 | 4.63E+05 | 17.66 |

## 5. Conclusions

Refinement of Hetsroni's approach for core flow distribution analysis was carried out and the derivation results were successfully applied to SFR mode design.

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