Chapter 7 Scaling and Modeling Laws in Two-Phase Flow and Boiling Heat Transfer

1. Importance of scaling

- not practical to build full size test facility
- Data from properly scaled tests can be easily scaled up to real situations.
- useful for the sensitivity study to improve the performance.
- impossible to observe the nuclear transients or accidents with a prototype model or real plant

2. Scaling Methodology

★ ┌ how facilities are scaled
  └ how the data are used

- dimensional analysis and similarity : geometrical, mechanical , static, dynamic, thermal, thermodynamic and electrical

  Reduction of number and complexity of experimental parameters which govern the concerned physical phenomena

  Generation of experimental results for various conditions with single experiment and non dimensional analysis instead of multi experiments

  predict and understand the phenomena and physical characteristics in prototype with similarity

(예)
$$S = S_o + V_o t + \frac{1}{2} g t^2 = f(t, S_o, V_o, g) \qquad (7.1)$$

From nondimensionalizing with

$$S^* = \frac{S}{S_o} \qquad t^* = \frac{V_o t}{S_o}$$

Eq. (7.1) will be

$$S^* = 1 + t^* + \frac{1}{2}\frac{gS_o}{V_o^2} t^{*2} = g(t^*, a), \quad \text{where } a = \frac{gS_o}{V_o^2} \qquad (7.2)$$

- Geometrical simularity when the prototype and the model have same scaling ratio for all three-dimensional lengths

  i) linear scaling : thermal and flow distribution distortion (specially in two phase flow)

  ii) volume scaling

- Dynamic simularity if the flow passes the corresponding position at scaled time in the prototype and the model

- Mechanical similarity if the force and pressure in the model proportionally coincide with those in the prototype

1 nondimensionalization of governing equations

o use of reference quantities

(예) $\rho\left(u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y}\right) = -\frac{\partial p}{\partial x} + \mu\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right)$

$\rightarrow U\frac{\partial U}{\partial X} + V\frac{\partial U}{\partial Y} = -\frac{\partial P}{\partial X} + \left(\frac{1}{Re}\right)\left(\frac{\partial^2 U}{\partial X^2} + \frac{\partial^2 U}{\partial Y^2}\right)$ for x *direction* (7.3)

o *Considerations*

- overlook the scaling for special components in overall scaling
- 각종 various assumptions included inherently in governing equations.
  - i) For single phase flow

    Governing equations for turbulent flow has the same form for the laminar flow with time averaging.

    Thus, need accurate description of laminar flow

    shear stress is related to molecular and "eddy".
  - ii) more complex in two phase flow (HEM, 2 fluid model and so on)

    uncertainties in balance equations, two phase flow correlations and flow regime transition criteria

    low α → HEM and higher α → complex model
- The general or universal governing equations excluding all assumptions are impractical or sometimes impossible to apply in the real system analysis.
  - difficult calculation of analytical eddy
  - empirical HTC from scaled experiment
  - lack of understanding and empirical database in two phase flow
  - limited range of application of model and correlation
- Since the scaling dimensionless parameters depend on the component, experimental conditions, type of transient, "perfect" scaling is only on the God's power.
- In the two phase flow which has complex and multiple phenomena, the scaling will be failed without additional descriptions for specific physical problems.

2 decide which processes in test loop are most important to preserve

- magnitude analysis with dimensionless conservation equation
- compare numerical coefficients multiplied by the differential form to other terms.

※ importance analysis of design parameters by pre calculation with code

3 design of scaled facilities

● *Two Prior Decisions*

1) **full height scale** (ROSA-LSTF, BETHY, SPES-1, etc)

ㄱ) Scaling analysis can be simplified.

ㄴ) 1:1 power to volume produces 1:1 time scale.

ㄷ) Volume reduction is inevitable.

ㄹ) The volume ratios in heat source and sink may be much larger than that in the prototype.

ㅁ) difficulty of scaling → ρ

ㅂ) widely used in the natural convection test

ㅅ) non prototypic influence of fluid properties
: void fraction, flow regime, bubble diameter

2) **reduced height scale**

ㄱ) prevent from over reduction of diameter

ㄴ) Most serious distortion in this method is the timing of event

ㄷ) But, benefit of saving time in the passive system experiment which has the long period transient

4) cost benefit analysis

5) using computer codes no scaling and analysis tools

3. Scaling in hydrodynamics and heat transfer

(1) Single phase

analogous in a diabatic flow if followings are similar.

1) the velocity field

2) the temperature field

3) the pressure field

typical dimensionless parameters : Re, Pr, Fr, Nu, Gr, Eu

(2) Two phase

○ add the phase distribution field

○ hydrodynamic and thermodynamic properties of both phase have to be similar
: bubble size vs pressure or rod space

○ Thus, in the two phase flow, the fluid scaling is more important than the geometry scaling.

4. Thermodynamic scaling of the fluids

○ density ratio : ρ_l/ρ_g (important in many hydro thermal-dynamic problems)

From Van der Weals equation,

$$\left(\frac{P}{P_c} + \frac{3}{v/v_c} \right) \left(3\frac{v}{v_c} - 1 \right) = 8\frac{T}{T_c} \qquad (7.1)$$

Saturated one component two phase flow, one thermodynamic properties can be fixed as

$$\left(\frac{P}{P_c}\right)_m = \left(\frac{P}{P_c}\right)_P, \quad \left(\frac{T}{T_c}\right)_m = \left(\frac{T}{T_c}\right)_P \cdot \quad \left(\frac{\rho}{\rho_c}\right)_m = \left(\frac{\rho}{\rho_c}\right)_P \cdot \quad \left(\frac{u}{u_c}\right)_m = \left(\frac{u}{u_c}\right)_P$$

, most useful for many applications (7.5)

◦ σ, μ, k are dominant parameters in bubble formation, flashing, entertainment.

 ✣ focus on scaling for one phase which controls the phenomenon

◦ For the flow pattern (i.e distribution of phases)

 1) If forces induced by ΔP prevail → annular flow

 2) If σ > forces from ΔP and buoyancy → bubbly flow

$$We = \frac{\rho v^2 D}{\sigma} \qquad \text{for annular flow}$$

$$N_{\text{bubbly flow}} = \frac{\sigma}{\rho g D^2}$$

◦ S and α ⇐ buoyancy forces and ΔP

$$Fr \left(= \frac{G}{g D_H \rho_s^2} \right)$$: scaling factor of ⟨α⟩

◦ Heat transfer with bubble formation at the wall ⇐ q'' or La

 But, the whole bubble boiling process is not well known

◦ interfacial mom and heat transfer ⇐ phase separation, drift flux, ⟨α⟩

5. Scaling of combined phenomena

In reactors, there are combined effects of several simple phenomena and link of fluid flow and heat transfer

• Consider blowdown test with Freon as simulant

geometrical scaledown, limited number of few rod bundle vs the total power

 ∴ use Freon

how to scale with respect to water

Due to such complicate blowdown phenonmena, the scaling by simple non dimensional parameters should be incorrect.

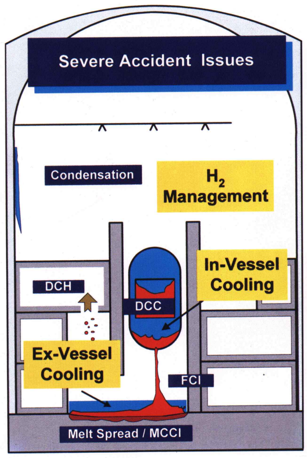
∴ develope the mathematical expression for a physical conception of T/H events.

Problems

1) rapid pressure reduction and very severe flashing

2) a very high acceleration to the break

∴ Freon loop : 0.1 bar of outside pressure of Fr loop
other problem for critical flow and heat storage
⇒ need detailed theoretical analysis.



• Scaling analysis for an experiment of passive decay heat removal from molten core by sump cooling in containment
o two phase natural circulation in short term
o single phase natural circulation in long term

<u>concerns</u>

◦ temperature/velocity field and flow pattern in coolant pool
◦ heat transfer mechanism along the core melt, heat exchanger and condensers
◦ influence of geometrical parameters

(1) Similarity group for single phase flow

Ri, Fi, St, Li, Ai

Characteristic velocity and temperature change scale can be deduced from the momentum and energy balance by Ishii & Kataoka

$$u_o = \left[\frac{2\beta g \dot{q}_o l_o^2}{\rho c_p \Sigma (F_i / A_i^2)} \right]^{1/3}$$

$$\Delta T_o = \frac{\dot{q}_o l_o}{\rho c_p u_o} \qquad (7.6)$$

Ri ← → pool mixing

St ← → heat transfer by heat exchanger

For the single pahse natural circulation,

$$Gr = \frac{\beta g \Delta T l_h^3}{\nu^2} \qquad : l_h : \text{ heater height}$$

$$Ra = GrPr \qquad (7.7)$$

For laminar natural circulation along vertical plate

$$N_u = \frac{h l_h}{k} = \frac{0.72 P_r^{1/2}}{(0.95 + P_r)^{1/4}} \left(\frac{Gr}{4} \right)^{1/4} \qquad (7.8)$$

For turbulent natural circulation, $N_u = 0.13\, R_a^{1/3}$ (7.9)

For vertical plate, the transition from laminar to turbulent heat transfer

$$10^9 < Ra_{crit} < 10^{10}$$

Characteristic time scale for charging or discharging heat.

$$\tau_c = \frac{\rho c_p (T_P - T_S)}{q} \qquad (7.10)$$

where $T_P - T_S$: ΔT between primary and secondary side of the system.

Time scale for steady state turn around time between heat source and heat sink

$$\tau_{o} = \frac{l_{o}}{u_{o}}$$

∴ dimensionless transient time scale. $\Pi_{t} = \frac{\tau_{o}}{\tau_{p}}$

› measure for the integral heat up or cooldown behavior of system.

◦ In the scaling model which uses the same fluid and geometrical simularity, the power and velocity should be reduced.
Then Gr will be seriously distorted between the model and the prototype, and there is a possibility that the turbulent flow in the prototype should be simulated by the laminar flow in the model.

∴ need adequate scaling of both geometry and power to maintain the turbulent flow in the model.

(2) two phase similarity group

N_{pch}, N_{sub}, N_{Fr}, N_{d}, N_{ρ}, N_{f}

N_{pch} : sump water 의 압력강하에 의한 phase change를 고려

N_{sub} : scale the subcooling of sump water entering heating section

— Both of dynamical and steady state conditions are important in the natural circulation scaling.

From steady state energy equation

$$N_{pch} = N_{sub} + x\frac{\Delta\rho}{\rho_{g}} \quad (7.11)$$

Note that N_{d} considers both of the flow pattern and the void fraction distribution.

6. Scaling criteria in nuclear thermal hydraulics

o linear scaling and volume scaling
o Ishii scaling criteria for single and two phase flow

(1) Scaling law by Carbiener and Cudnik

◦ For large LOCA
◦ two volumes which represent upper and lower space from core, and connecting path of core

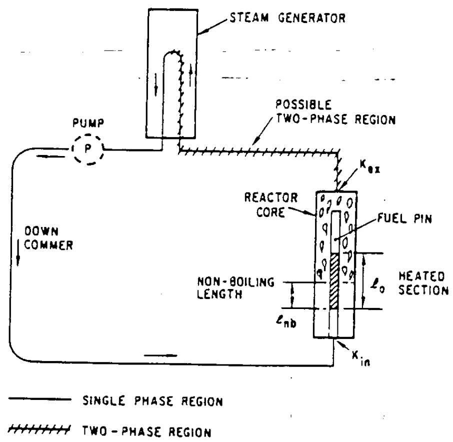


Fig. 1.1 LWR Natural Circulation

- two criteria
  1. time preserving scaling

     volime scaling : preserve the break area and power corresponding to volume scaling the same blowdown time of model as that in prototype

     but larger flow resistance in core for the model
  2. time reducing scaling

     linear scaling : reduced copy of prototype

     In this scaling, the acceleration may increases when the velocity is preserved. Thus, if the gravitational acceleration during blowdown is important it is practically impossible to conduct the experiment since we need larger gravity.

	time preserving volume scale	time reducing linear scale
Blowdown time, $t_R = t_m/t_p$	1	l_R
Upper volume, V_{1R}	$l_R^{[illegible]}$	$l_R^{[illegible]}$
Lower volume, V_{2R}	$l_R^{[illegible]}$	$l_R^{[illegible]}$
Core length, L_{cR}	$l_R^{[illegible]}$	l_R
Core flow area, a_{cR}	$l_R^{[illegible]}$	$l_R^{[illegible]}$
Break area, a_{bR}	$l_R^{[illegible]}$	$l_R^{[illegible]}$
Core power, q_{cR}	$l_R^{[illegible]}$	$l_R^{[illegible]}$
Core flow resistance, K_{cR}	$1/l_R^{[illegible]}$	$1/l_R^{[illegible]}$

※ l is the characteristic length of two volume and

$l_R = l_{model}/l_{prototype}$ = scale factor.

(2) Nahavandi scaling law

- reopganization Carbiener and Cudnik's time reducing scaling law with the equation of state and three dimensional conservation equations
- developed time preserving scaling law of different form of Carbiener and Cudnik' law

1) linear scaling law

Using the following nondimensional parameters as,

$$x_i^* = x_i/l_o\ ,\qquad u_i^* = u_i/u_o\ ,\qquad t^* = tu_o/l_o\ ,$$
$$F_i^* = F_i/g\ ,\qquad p^* = p/\ p_o\ ,\qquad \rho^* = \rho/\rho_o\ , \tag{7.12}$$
$$T^* = T/\ T_o\ ,\qquad h^* = h/C_p\ T_o\ ,\qquad \beta^* = \beta\ T_o\ .$$

nondimensionalize the quation of state and three dimensional conservation equations.

Then, we can obtain the following 1 additional non dimensional parameters to 9 non dimensonal parameters of Carbiener and Cudnik's scaling law.

$$\frac{u_o^2}{g l_o}(Fr),\quad \frac{\Delta p_o}{\rho_o u_o^2}(Eu),\quad \frac{\Delta p_o}{\rho_o C_p \Delta T_o}(Eu \cdot Er),\quad \frac{\dot{q}''' l_o}{\rho_o u_o C_p \Delta T_o}(\text{Heat Source No}) \qquad (7.13)$$

If the operation pressure, temperature and working fluid are preserved in the model, the following 6 parameters automatically satisfy the above scaling criteria.

$$u^*,\ \rho^*,\ T^*,\ h^*,\ p^*,\ \text{and}\ \frac{\Delta p_o}{\rho_o C_p \Delta T_o}$$

If the scale factor is l_{oR} ($= l_{om}/l_{op}$), the scaling criteria is given as,

$$
\begin{aligned}
\frac{p_o}{\rho_o u_o^2} &\rightarrow u_{oR} = 1 \\
u_i^* &\rightarrow u_{iR} = 1 \\
t^* &\rightarrow t_R = l_{oR} \\
\frac{u_o^2}{g l_o} &\rightarrow g_R = 1/l_{oR} \\
\frac{\dot{q}''' l_o}{\rho_o u_o C_p \Delta T_o} &\rightarrow \dot{q}_R''' = 1/l_{oR}
\end{aligned}
\qquad (7.14)
$$

· <u>Nahabandi's time reducing scaling law</u>

- In this time preserving scaling, the model shouldn't be a geometrical copy of the prototype.
- Since the power is scaled by the volume, Nahabandi called this method as the volume scaling law. But, generally, the volume scaling is Nahabandi's time preserving scaling.
- Volume scaling requires "full height" in the model.
- Thus, fl/d should be preserved in the model since the reduction of diameter increases the flow resistance which can be measured by fl/d.

(3) One dimensional single phase scaling without the wall heat transfer

For i th node of natural circulated loop without the wall heat transfer in PWR,

$$u_i = \frac{a_r}{a_i} u_r \qquad (7.15)$$

$$\rho \frac{du_r}{dt} \sum_i \frac{a_r}{a_i} l_i = \beta g \rho \Delta T l_h - \frac{\rho u_r^2}{2} \sum_i \left(\frac{fl}{d} + K\right)_i \left(\frac{a_r}{a_i}\right)^2 \qquad (7.16)$$

$$\rho C_p\left(\frac{\partial T_i}{\partial t} + u_i\frac{\partial T_i}{\partial x}\right) = \dot{q}''' \qquad (7.17)$$

where l_h = equivalent total length of the hot fluid sections

u_r is the velocity at the flow area a_r during the steady state natural circulation and u_o is the reference velocity.

$u_i^* = u_i/u_o$, $u_r^* = u_r/u_o$, $a_i^* = a_i/a_o$,

$l_i^* = l_i/l_o$, $l_h^* = l_h/l_o$, $x^* = x/l_o$,

$t^* = tu_o/l_o$, $T^* = T/\Delta T_o$, $\Delta T^* = \Delta T/\Delta T_o$.

→ Richardson number $\quad Ri = \dfrac{g\beta\Delta T_o l_o}{u_o^2}$.

friction/orifice number $\quad Fi = \dfrac{fl}{d} + K$.

heat source number $\quad Q = \dfrac{\dot{q}''' l_o}{\rho C_p u_o \Delta T_o}$.

For a fluid(ρ_R = 1) of same pressure and temperature as the prototype,

$a_{iR}^* = 1$ → flow area simularity

$l_{iR}^* = l_{hR}^* = x_R^* = 1$ → simularity of length and height

$t_R^* = 1$ → $t_R = (l_o/u_o)$

$T_R^* = 1$ → $T_R = (\Delta T_o)$

$R_R = 1$ → $(\Delta T_o)_R = u_{oR}^2/l_{oR}$ $\qquad (7.18)$

$F_R = 1$ → *preservation of flow resistance*

$Q_R = 1$ → $\dot{q}_R''' = u_{oR}^3/l_{oR}^2$.

- <u>fluid property matching</u> : $T_R = 1$ (or $(\Delta T_o)_R = 1$)
- <u>Richardson number matching</u> : $u_{oR} = (l_{oR})^{1/2}$ $\qquad (7.19)$
- <u>time and hear source scaling</u> for fixed u_o , l_o

$$t_R = (l_{oR})^{1/2} \qquad (7.20)$$

$$\dot{q}_R''' = (l_{oR})^{-1/2} \qquad (7.21)$$

➡ <u>a principal results of Ishii scaling</u>

★ If l_{oR} = 1 (full hight model), this scaling becomes a volume scaling.

★ And when u_{oR} = 1 for Richardson number, the time and heat source number scaling will be,

$$t_R = l_{oR} \quad \text{and} \quad \dot{q}_R''' = (l_{oR})^{-1}$$

– : linear scaling

∴ Linear seling is a special kind of Ishii scaling method.

(4) **One dimensional single phase scaling with the wall heat transfer**

fluid energy equation

$$\rho C_p\left(\frac{\partial T_f}{\partial t}+u_f\frac{\partial T_f}{\partial x}\right)=\frac{4h}{d_f}(T_s-T_f) \tag{7.22}$$

solid energy equation

$$\rho_s C_{ps}\frac{\partial T_s}{\partial t}+k_s\nabla^2 T_s=\frac{a_f}{a_s}\frac{4h}{d_f}(T_f-T_s)+\dot{q}_s''' \tag{7.23}$$

boundary condition

$$k_s\frac{\partial T_s}{\partial y}=h(T_s-T_f) \tag{7.24}$$

Then, nondimensional governing equations will be.

$$u_i^*=u_r^*/a_i^* \tag{7.25}$$

$$\frac{du_r^*}{dt^*}\sum_i\frac{l_i^*}{a_i^*}=\frac{g\beta\Delta T_o l_o}{u_o^2}\Delta T^* l_h^*-\frac{u_r^{*2}}{2}\sum_i\frac{(fl/d+K)}{a_i^{*2}} \tag{7.26}$$

$$\frac{\partial T_f^*}{\partial T^*}+u_i^*\frac{\partial T_f^*}{\partial x^*}=\frac{4hl_o}{\rho C_p u_o d_i}(T_s^*-T_f^*) \tag{7.27}$$

$$\frac{\partial T_s^*}{\partial t^*}+\frac{h^2 l_o}{k_s\rho_s C_{ps}u_o}\left(\frac{\partial^2 T_s^*}{\partial y^{*2}}+\frac{\partial^2 T_s^*}{\partial z^{*2}}\right)+\frac{k_s}{\rho_s C_{ps}u_o l_o}\frac{\partial^2 T_s^*}{\partial x^{*2}}$$

$$=\frac{a_f}{a_s}\frac{sh}{d}\frac{l_o}{\rho_s C_{ps}u_o}(T_f^*-T_s^*)+\frac{\dot{q}_s''' l_o}{\rho_s C_{ps}u_o\Delta T_o} \tag{7.28}$$

and

$$-\frac{\partial T_s^*}{\partial y^*}=T_s^*-T_f^* \qquad \text{at interface} \tag{7.29}$$

Above nondimensional equations produce new nondimensional parameters as,

modified Stanton number $\qquad St=\frac{4hl_o}{\rho C_p u_o d}$

lateral conduction parameter $\qquad LC=\frac{h^2 l_o}{\rho_s C_{ps}k_s u_o}$

streamwise conduction paramter $\qquad SC=\frac{k_s}{\rho_s C_{ps}u_o l_o}$

and $\qquad \frac{a_f}{a_s}\frac{4hl_o}{\rho_s C_{ps}u_o d}$

Last nameless parameter means,

$$\left(\frac{4hl_o}{\rho C_p u_o d}\right)\left(\frac{a \rho C_p}{a_s \rho_s C_{ps}}\right) = \frac{\text{modified Stanton number}}{\text{thermal mass ratio}}$$

For identical fluid-metal modeling,

i) $(SC)_R = (u_{oR} l_{oR})^{-1} = (l_{oR})^{-3/2}$ (7.30)

∴ only preserved in the model of full height

ii) St and LC

: include h, which depends not only on fluid properties but also D and v

From Dittus-Boelter equation,

$$h_R = (u_{oR})^{0.8} (d_R)^{-0.2}$$

Thus, $(St)_R = h_R l_{oR} / (u_{oR} d_R) = (l_{oR})^{0.9} (d_R)^{-1.2}$

$(LC)_R = h_R^2 l_{oR} / u_{oR} = (l_{oR})^{1.3} (d_R)^{-0.4}$

∴ Even in the full height model, St or LC can't be preserved since d_R is normally much less than 1 and thus $(St)_R$ and $(LC)_R$ may be larger than 1.

Consider

$$LC = \frac{l_o / u_o}{\rho_s C_{ps} k_s / h^2} = \frac{\text{moving time in flow direction}}{\text{heat transport time fram wall}}$$

Thus, since $(St)_R$ and $(LC)_R$ are larger than 1, the effect of solid wall temperature may be overestimated. That means the temperature difference between wall and fluid in the prototype will be less than those in the model.

★ Scaling Criteria for PWR single-phase natural circulation by Ishii

1. $a_{iR} = \left(\frac{a_i}{a_o}\right)_R = 1.$: flow area similarity
2. $l_{iR} = \left(\frac{l_i}{l_o}\right)_R = 1.$: length or height similarity
3. $F_R = \left(\frac{fl}{d} + K\right)_R = 1.$: component flow resistance similarity
4. $\left(\frac{a_{si}}{a_i}\right)_R = 1.$: wall cross-sectional area similarity
5. $\rho_R = C_{pR} = \ldots = 1.$: fluid property simularity
6. $p_R = T_R = 1.$: same operating pressure and temperature
7. $\dot{q}_R''' = (l_{oR})^{-1/2}.$: increased power density in the model
8. $u_{oR} = (l_{oR})^{1/2}$
9. $t_R = (l_{oR})^{1/2}$
10. $\Delta T_R = 1.$

√ This kind of scaling criteria can't be applied to all nondimensional parameters (ex : St, LC, SC).

√ Real time scaling is improper.

That is, to obtain $t_R = 1$, $\mu_{oR} = l_{oR}$ $\therefore$ $\Delta T_R = l_{oR}$ and $T_R = l_{oR}$

In this case, the mismatch of temperature inevitably yields the distortion of fluid property.

Example(real time simulation)

For simulation of a natural circulation in System 80 by LOFT

$$l_R = 0.4 \qquad (7.31)$$

Thus, for a real time simulation,

$$u_R \sim 0.1 , \qquad q_R \sim 0.1$$

However, $\delta_R = d_R \sim 1$

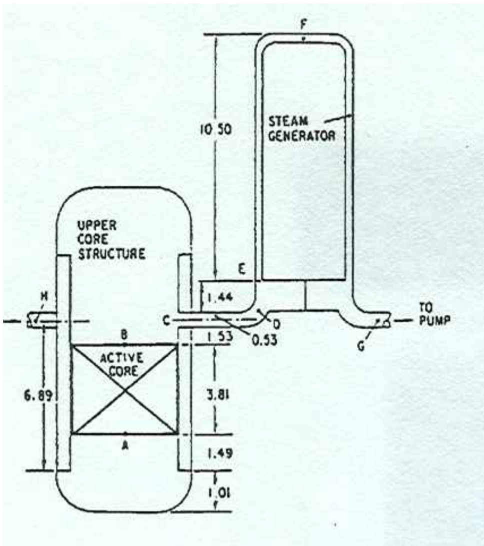


그림 1.2 Simplified PWR Geometry

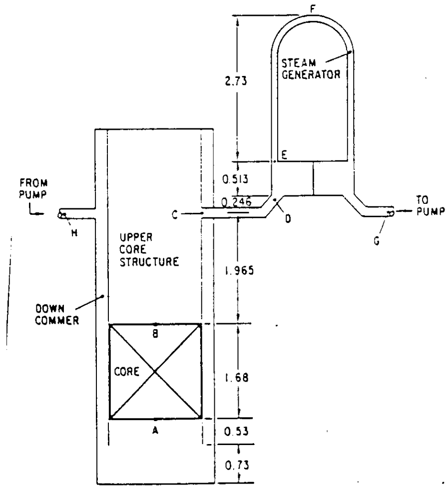


그림 1.3 Simplified LOFT Geometry

Table 1.1 show the values of scaled parameters in the LOFT facility for natural circulation. Since the length ratio of S/G tube is 0.26, we can expect unreliable results for rapid power change.

Item		System	
		PWR	LOFT
Fuel rod O.D.	(cm)	0.97	1.07
length (AB)	(cm)	381	168
pitch	(cm)	1.29	1.43
Hydraulic diameter	(cm)	1.2	1.363
Number of rods		~ 55000	1300
Elevation BC	(cm)	158	196.5
Elevation CE	(cm)	197	75.9
Elevation EF	(cm)	1050	273
SG tube I.D.	(cm)	1.69	1.02
Wall thickness	(cm)	0.107	0.124
Number of tubes		~ 11000	1845

표 1.1 Scaled Parameters in LOFT

(5) Two Phase Simulality

based on the drift flux model

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial z}(\rho_m u_m) = 0$$

$$\frac{\partial(\alpha\rho_g)}{\partial t} + \frac{\partial}{\partial z}(\alpha\rho_g u_g) = \Gamma_g - \frac{\partial}{\partial z}\left(\frac{\alpha\rho_g\rho_f}{\rho_m}V_{gj}\right)$$

$$\frac{\partial(\rho_m u_m)}{\partial t} + \frac{\partial}{\partial z}(\rho_m u_m^2) = -\frac{\partial p_m}{\partial z} - \rho_m g - \frac{\partial}{\partial z}\left(\frac{\alpha\rho_g\rho_f}{(1-\alpha)\rho_m}V_{gj}^2\right) - \left(\frac{f_m}{2D} + \frac{K}{2}\delta(z-z_i)\right)\rho_m u_m|u_m|$$

$$\frac{\partial(\rho_m H_m)}{\partial t} + \frac{\partial}{\partial z}(\rho_m u_m H_m) = \frac{4h_w}{d}(T_w - T_{sat}) - \frac{\partial}{\partial z}\left(\frac{\alpha\rho_g\rho_f}{\rho_m}H_{fg}V_{gj}\right)$$

$$\rho_s C_{ps}\frac{\partial T_s}{\partial t} + k_s\nabla^2 T_s + \dot{q}_s = 0$$

$$k_s\frac{\partial T_s}{\partial y} = h_m(T_s - T_{sat})$$

additional constitute equations for V_{gj}, C_o, CHF, void - quality correlation, etc

nondimensional parameters for two phase flow

phase change number $N_{pch} = \frac{\dot{q}''' l_o}{\rho_f u_o \Delta h_{fg}}\frac{\Delta\rho}{\rho_g}$: scale for amount of heat and phase change

subcooling number $N_{sub} = \frac{\Delta H_{sub}}{\Delta H_{fg}}\frac{\Delta\rho}{\rho_g}$: scale for the cooling in the condensation section

Froude number $N_{Fr} = \frac{u_o^2}{g l_o \langle\alpha\rangle_o}\frac{\Delta\rho}{\rho}$

drift flux number $N_d = \frac{u_{gj}}{u_o}$

density ratio $N_\rho = \frac{\rho_g}{\rho}$

friction number $N_f = \frac{fl}{d}\left(\frac{1+x\Delta\rho/\rho_g}{(1+x\Delta\mu/\mu_g)^{0.25}}\right)\left(\frac{a_o}{a_i}\right)^2$

orifice number $N_o = K(1 + x^{1.5}\rho_f/\rho_g)(a_o/a_i)^2$

CHF number $N_q = q_c''/q_o''$

time ratio $T_i = \left(\frac{\alpha_s}{\delta^2}\frac{l_o}{u_o}\right)$

heat source number $Q_i = \left(\frac{\dot{q}_s''' l_o \Delta\rho_{fg}}{\rho_s c_s u_o \Delta H_{fg} \rho_g}\right)$

modification with correlations

(ex) $N_d = 0.2(1 - \sqrt{\rho_g/\rho_f})\left(1 + \frac{\Delta\rho x}{\rho_g}\right) + \frac{1.41}{u_o}\left(\frac{\sigma g \Delta\rho}{\rho_f^2}\right)^{1/4}$

I. scaling model with same fluid (same fluid properties)

$$\rho_R = \rho_{gR} = \beta_R = C_{pR} = k_R = \mu_R = \mu_{gR} = \Delta H_{fgR} = 1$$

Then,

$$(N_{pch})_R = \frac{\delta_R q_R l_R}{d_R u_R} = 1 \ , \ (N_{sub})_R = \Delta H_{subR} = 1 \ , \ (N_{Fr})_R = \frac{u_R^2}{l_R \langle a \rangle_R} = 1$$

$$(N_f)_R = \left(\frac{fl}{d}\right)_R \left(\frac{a_o}{a_i}\right)_R^2 = 1 \ , \quad (N_o)_R = K_R\left(\frac{a_o}{a_i}\right)_R^2 = 1$$

- From large relative motion, N_d is automatically satisfied except the case that the local slip is dominant. And $\alpha_R = 1$
- From the single phase criteria on geometry,

$$u_R = \sqrt{l_R} \quad , \quad q_R = \frac{1}{\sqrt{l_R}} \qquad (7.32)$$

  satisfy single phase criteria on the velocity.
- Also, in Eq. (7.32), the power in the model should be increased.
- $(N_f)_R$

  ∵ In real cases, it is hard to significantly reduce the length ratio than the diameter ratio. i.e large $(N_f)_R$

  ∴ Need caseful treatment of $(N_f)_R$ and $(N_o)_R$

<u>Sample Example</u>

From Eqs. (7.31) and (7.32)

$l_R \approx 0.1$, $u_R \approx 0.6$, $q_R \approx 1.5$ (약 50% higher power in LOFT)

Then $\delta_R = d_R = 0.8$, $(\Delta H_{sub})_R = 1$

And $\left(\frac{fl}{d}\right)_R = 1$, $K_R = 1$, $t_R = l_R/u_R \approx 0.6$

∴ the time events will be accelerated in the model.

2) scaling using reduced system pressure

i) time scale simulation

$$(\tau_R)_{sp} = (\tau_R)_{tp} = l_{oR}^{1/2}$$

From. Eq. (3), $(\beta \rho_s h_{fg}/\Delta\rho c_p \zeta)_R = 1$ (7.33)

∴ impossible to satisfy the above equation for modeling high pressure systems with low pressure model using the same fluid.

ii) power scale

From Eq. (1),

$$(\dot{q}'''_{oR})_{sp} = (\dot{q}''')_{tp} = (\rho_s \rho_g h_{fg}/\Delta\rho)_R (\rho_s c_{ps})/(\rho_s c_{ps})_R\, l_{oR}^{1/2}$$

also can not satisfy Eq. (7.33)

cause different time scales in single phase and two phase flow.

geometric distortions caused by power scaling may nat be significant.

☞ Ishii scaling is an well known scaling. But in many two phase cases, the generality is in doubt.

☞ Ishii scaling doesn't need a full height model.

☞ If the full height model is used, Ishii의 scaling becomes Nahabandi's volume scaling.

☞ In volume scaling, fl/a scale is difficult.

☞ When the fluid properties are dependant on the temperature, Ishii's time preserving scaling may yield some problems.