Similarity Assessment of Engineering Designed Small Scaled Sodium Integral Test Facility

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1. Introduction

According to a domestic long-term nuclear program plan, a prototype sodium-cooled fast reactor is scheduled to be constructed by 2028. To support the program plan, a large-scale sodium thermal–hydraulic test program called STELLA (Sodium Test Loop for Safety Simulation and Assessment) is being progressed by KAERI (Korea Atomic Energy Research Institute). This study is on the engineering design of integral test facility for prototype reactor PGSFR (Prototype Gen-IV Sodium-cooled Fast Reactor). PGSFR is a kind of Gen-IV reactor, and its thermal power is 392.2MWth and electric power is 150MWe[1].

The small scaled integral test facility is to be design with linear scale 1/5, and the same aspect ratio[2]. According to this requirement, an engineering design was carried out on the base of Ishii et al.'s scale law [3] in this study. The verification of the engineering design was conducted using MARS-LMR code [4] according to the guide line of Ransom et al.[5].

2. Engineering Design of Integral Test Facility

2.1 Scaling Analysis

For single phase phenomena, Ishii et al.'s scaling law requires following dimensionless numbers to be conserved both in prototype and model.

- Richardson Number:

$$R \equiv \frac{\beta g \Delta T_0 l_0}{u_0^2} = \frac{\text{buoyancy}}{\text{inertia force}} \tag{1}$$

- Friction Number:

$$F_i \equiv \left(\frac{fl}{D_H} + K\right)_i = \frac{\text{friction}}{\text{inertia force}} \tag{2}$$

- Modified Stanton Number:

$$St \equiv \frac{4hl_0}{u_0 \rho c_p D_H} = \frac{\text{wall convection}}{\text{axial convection}} \tag{3}$$

- Time Ratio Number:

$$T^* \equiv \frac{\alpha_s l_0}{\delta^2 u_0} = \frac{\text{transport time}}{\text{conduction time}} \tag{4}$$

- Heat Source Number:

$$Q_s \equiv \frac{\dot{q}_s''' l_0}{\rho_s c_{p,s} T_0 u_0} = \frac{\text{heat source}}{\text{axial energy change}} \tag{5}$$

- Biot Number:

$$Bi \equiv \frac{h\delta}{k_s} = \frac{\text{wall convection}}{\text{conduction}} \tag{6}$$

However, it is almost impossible to conserve all of the above dimensionless numbers, in particular, it is actually impossible to conserve the modified Stanton number and the Biot number at the same time. Thus, in this study the modified Stanton number was preferentially conserved, and then the distortion of the Biot number was checked.

Table I: Global scaling factor

Parameter	Scaling law	Values ($\Delta T_{0,R}^{1/2} = 1$)
Length ratio	$l_{0,R}$	1/5
Area ratio	$l_{0,R}^2$	1/25
Volume ratio	$l_{0,R}^3$	1/125
Hydraulic diameter ratio	$\frac{l_{0,R}^2}{\xi_R} = l_{0,R}$	1/5
Velocity ratio	$\Delta T_{0,R}^{1/2} l_{0,R}^{1/2}$	1/2.2
Time ratio	$\frac{l_{0,R}^{1/2}}{\Delta T_{0,R}^{1/2}}$	1/2.2
Wall thickness ratio	$\alpha_{s,R}^{1/2} l_{0,R}^{1/4}$	1/1.5
Power density ratio	$l_{0,R}^{-1/2}$	1/0.45
Power ratio (heat transfer between fluid and solid)	$l_{0,R}^{5/2}$	1/55.9

Important global scaling factors are listed in Table I.

2.2 Engineering Design of Core

Model core was simulated using electrical heater. In order to overcome the material composition differences in prototype and model, equivalent thermal property formula were derived [6], and the electrical heater design was performed. Fig 1 is Prototypic core and arrangement of fuel assembly. Table II provides fuel and core design parameters.

Table III is specification of the designed model heater, and Fig. 2 is the model heater rod shape. Figs. 3 and 4 is the arrangement of heater and assembly in model.

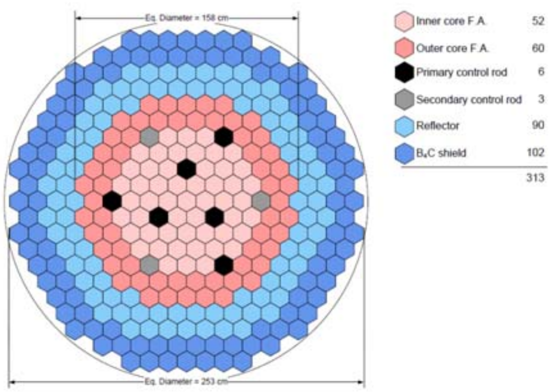

Fig. 1. Prototypic core and arrangement of fuel assembly.

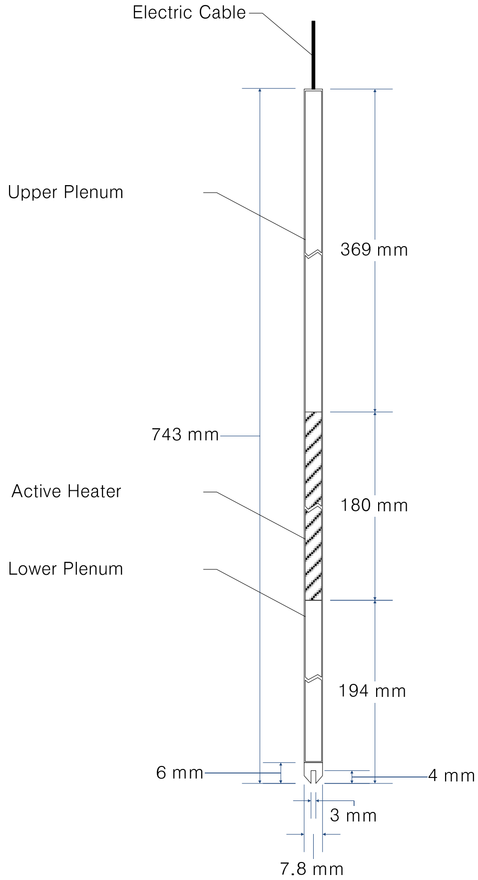

Fig. 2. Model heater.

Table II: Prototypic fuel and core design parameters

Rod pin diameter		7,406
Active Core Height [mm]		900
Number of Assemblies	Inner Driver Fuel	52
	Outer Drive Fuel	60
	Reflector	90
	B4C Shield	102
	Control Rod (Primary/Secondary)	6/3

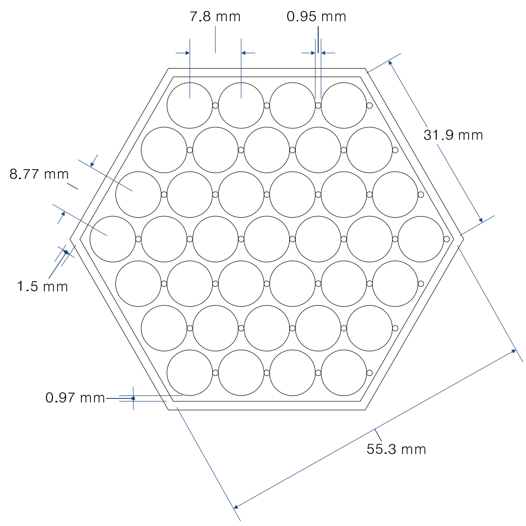

Fig. 3. Heater rod arrangement in assembly.

Table III: Model electric heater design

Comp.	Core	Heat Source	Insulator	Sheath
Material	BN	NiCr	BN	Stainless Steel
Thickness [mm]	3.133	0.1012	0.35	0.316

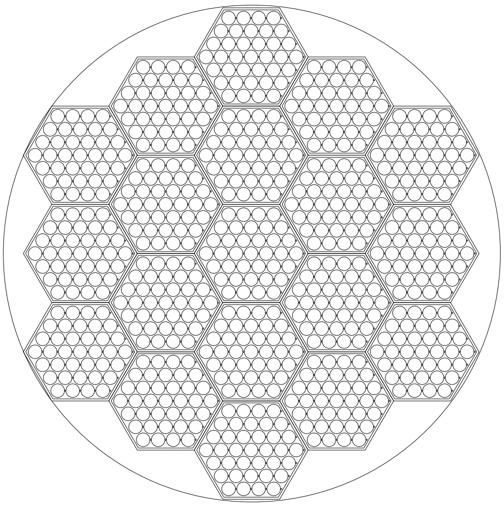

Fig. 4. Arrangement of model heater assembly.

2.3 Engineering Design of Reactor and Loops

The other parts of reactor were designed according to the base length scale. And the pressure drop was designed so as to conserve the friction number.

3. Similarity Assessment

Loss of flow (LOF) was selected for the similarity assessment between prototype and model. At first prototypic LOF was analyzed using MARS-LMR code [4], and then model LOF was analyzed to compare each other. Of course, the best method for similarity assessment for the designed facility is to conduct the same transient in two facility of different scale. However, such a method is too expensive and not

Table IV: Steady result in the model

	Plant Parameter	Prototype	Model-design	Model-Calculated
PHTS	Core power [MWt]	401.949	7.159	7.159
	Upper cover gas pressure (C240) [bar]	1.0133	1.0133	1.0133
	Core pressure drop (C168~C196)[bar]	4.027	0.805	0.836
	Average core flow (through C175) [kg/s]	1904.1	1904.4	
	Hot driver flow (through C178) [kg/s]	18.04	18.04	
	Control rod-reflector-b4c flow (through C180) [kg/s]	22.1	22.0	
	Leakage flow (through C190) [kg/s]	45.0	45.2	
	Total core flow (J197)	1989.2	35.6	35.7
	Hot pool center temperature (C21001) [K]	830.2	830.2	829.1
	IHX lower head temperature (C265) [K]	671.39	671.39	672.00
	IHX lower head temperature (C275) [K]	671.39	671.39	672.00
	IHX lower head temperature (C285) [K]	671.39	671.39	672.00
	IHX lower head temperature (C295) [K]	671.39	671.39	672.00
	IHX 1 shell flow (C26002) [kg/s]	498.01	8.91	8.96
	IHX 2 shell flow (C27002) [kg/s]	498.01	8.91	8.96
	IHX 3 shell flow (C28002) [kg/s]	498.01	8.91	8.96
	IHX 4 shell flow (C29002) [kg/s]	498.01	8.91	8.96
	DHX 1/2 shell inlet temperature (C10002) [K]	696.21	663.15	669.31
	DHX 1 shell outlet temperature (C24210) [K]	608.07	626.15	621.15
	DHX 2 shell outlet temperature (C25210) [K]	618.21	626.15	626.68
	DHX 1 shell temperature drop [K]	88.14	37.00	48.16
	DHX 1 shell temperature drop [K]	78.00	37.00	42.63
	DHX 1 shell flow (J24202) [kg/s]		0.11	0.11
	DHX 2 shell flow (J25202) [kg/s]		0.11	0.11
	Inlet plenum (C168) [K]	671.65	671.65	671.54
	Temperature Rise (C210~C168)[K]	158.55	158.55	157.60
	Pump discharge flow (C115) [kg/s]	994.79	17.80	17.84
	Pump discharge flow (C145) [kg/s]	994.79	17.80	17.84
	Inlet plenum inflow (C130) [kg/s]	497.4	8.90	8.92
	Inlet plenum inflow (C135) [kg/s]	497.4	8.90	8.92
	Inlet plenum inflow (C160) [kg/s]	497.4	8.90	8.92
	Inlet plenum inflow (C165) [kg/s]	497.4	8.90	8.92
	Primary side IHX pressure drop (C21001~C265) [bar]	-0.297	-0.059	-0.053
IHTS	Expansion tank pressure (C39402) [bar]	1.584	1.584	1.505
	IHTS pump flow (C380) [kg/s]	747.3	13.4	13.3
	IHTS pump flow (C480) [kg/s]	747.3	13.4	13.3
	IHX lower chamber flow (C30501) [kg/s]	373.64	6.7	6.7
	IHX lower chamber flow (C35501) [kg/s]	373.64	6.7	6.7
	IHX lower chamber flow (C40501) [kg/s]	373.64	6.7	6.7
	IHX lower chamber flow (C45501) [kg/s]	373.64	6.7	6.7
	IHX lower chamber temperature (C305) [K]	597.289	597.289	599.047
	IHX lower chamber temperature (C355) [K]	597.289	597.289	599.047
	IHX lower chamber temperature (C405) [K]	597.289	597.289	599.047
	IHX lower chamber temperature (C455) [K]	597.289	597.289	599.047
	IHX upper plenum temperature (C31501) [K]	808.586	808.586	809.36
	IHX upper plenum temperature (C36501) [K]	808.586	808.586	809.36
	IHX upper plenum temperature (C41501) [K]	808.586	808.586	809.36
	IHX upper plenum temperature (C46501) [K]	808.586	808.586	809.36
	IHX temperature rise (C305~C31501) [K]	211.297	211.297	210.313
	IHX temperature rise (C355~C36501) [K]	211.297	211.297	210.313
	IHX temperature rise (C405~C41501) [K]	211.297	211.297	210.313
	IHX temperature rise (C455~C46501) [K]	211.297	211.297	210.313
DRS	DRS 1 tube flow (C60002) [kg/s]	7.307	0.15	0.13045
	DRS 2 tube flow (C70002) [kg/s]	12.278	0.15	0.15002
	AHX inlet Na Temperature (C61605) [K]	679.764	653.15	657.90
	FHX inlet Na Temperature (C71501) [K]	667.528	653.15	655.95
	AHX outlet Na Temperature (C62001) [K]	592.877	625.15	610.30
	FHX outlet Na Temperature (C71901) [K]	614.16	625.15	619.17
	AHX Na temperature drop [K]	86.887	28	47.60
	FHX Na temperature drop [K]	53.368	28	36.78

practical, Ransom et al proposed an approximate assessment method using best estimate thermal hydraulic code such as MARS-LMR[4]. The similarity assessment in this study is based on this suggestion.

3.1 Prototypic LOF analysis

The most severe accident in prototypic PGSFR is believed to be loss LOF. The LOF transient was taken from KAERI's analysis.

3.2 Model LOF analysis

Input preparation

Core and heat exchanger such as IHX and DHX were especially design and the corresponding inputs were composed actually. And the other parts are roughly input according to scaling law. However, such an approach is expected to arise negligible effect on overall behaviors.

Steady state calculation

The power in model was assumed 100%. Such a simulation is expected to give more exact insight on the model behaviors. After this assessment of 100%, 7% power will be assessed.

The calculated steady state is given in Table IV. All parameters show good matches but DHX heat removal. This should be more carefully investigated later.

LOF calculation

The simulated core decay heat is shown in Fig. 5. The calculated core inlet and outlet sodium temperature is given in Fig. 6. It shows good similarity between model and prototype. The fuel temperature in Fig. 7 also shows relatively good similarity. The difference in the earlier phase is thought to be caused by the difference in initial steady state by the difference of heat source

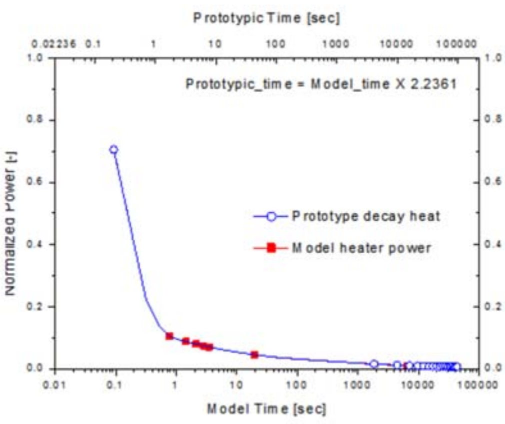

Fig. 5. Normalized decay heat input in model.

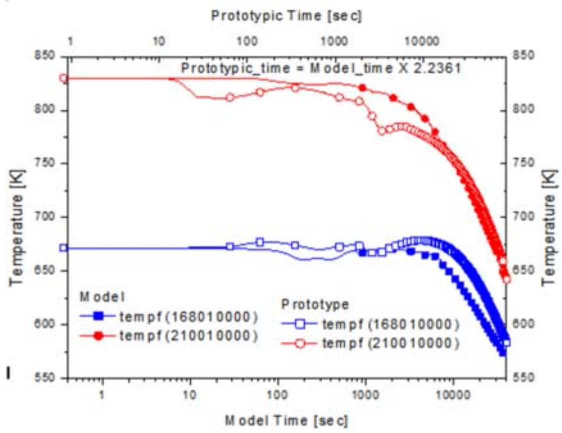

Fig. 6. Core inlet and outlet temperature in model and prototype.

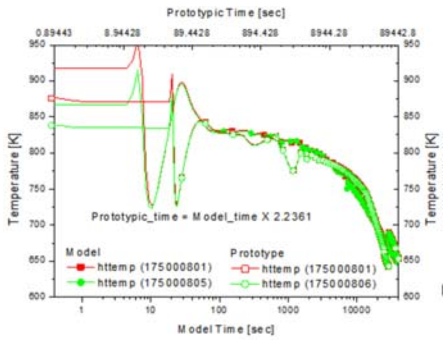

Fig. 7. Fuel temperature in model and prototype.

4. Conclusions

Engineering design based on Ishii et al.'s scale law and equivalent thermal property leads good similarity between model and prototype. Slight difference in fuel temperature need additional review and assessment.

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