Scaling analysis and Heat removal system design of the Sodium Thermal-hydraulic Experimental Facility

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1. Introduction

One of the most important tasks in the successful design of a Sodium-cooled Fast Reactor (SFR) is the demonstration of safe and reliable decay heat removal (DHR). To this end, a large-scale sodium thermal-hydraulic experimental facility (STEF) is currently being designed for verifying the innovative design concept of the Passive Decay Heat Removal Circuit (PDRC) which is the passive safety-grade decay heat removal system of KALIMER-600 [1].

The objective of the experiment has been focused on assessing the shutdown heat removal capability of the PDRC system. The test scope also covers the dynamic simulation of the natural circulation flow of sodium and relevant heat transfer phenomena during a transient mode.

Since the PDRC system involves unique features and very complex geometry and configuration, the optimum scale model that will correctly simulate the performance of the full-scale system with reasonable cost becomes the vital factor to the test facility design.

This study introduces the reasonable scaling methods generally implemented in large-scale thermo-hydraulic test facilities and provides the key design data of the scaled PDRC system and relevant components with reasonable scaling analysis results. The scaling distortion deviated from the prototype full-scale PDRC system was discussed as well.

2. Methods and Results

2.1 Overall scaling approach

The PDRC system is comprised of tertiary heat transport system including the PHTS (Primary Heat Transport System), the PDRC loop system and the AHX (sodium-Air Heat eXchanger) shell-side air path [2]. In order to model these coupled heat transport systems, the reduced-scale test facility has been designed complying with the proper scaling criteria for geometric, hydrodynamic and thermal similarities to preserve major thermal-hydraulic phenomena in the prototype PDRC system.

Based on the survey result of the various scaling methods regarding a suitable simulation for single-phase (sodium) natural circulation phenomena, Ishii's three-level scaling approach [3] has been implemented in the reduced test facility design. The scaling analysis approach is based on the mathematical identity of analogous physical systems, and the specific dimensionless variables and parameters used in the similarity study were derived from the dimensionless conservation equations of the system [4]. The similarity criteria were obtained from the condition of the same dimensionless groups between the model (test facility) and the prototype (KALIMER-600) for the given volume and length scales. The general scaling criteria is shown in Table 1 [5].

Table 1. General scaling criteria

Parameter	Symbol	Scaling Ratio (Model/Prototype)	
		Expression	Design Data
Length Ratio	l_R	l_R	1/5
Area Ratio	a_R	a_R	1/25
Volume Ratio	V_R	$l_R \times a_R$	1/125
Temperature distribution	ΔT_R	–	1
Velocity Ratio	u_R	$l_R^{1/2}$	1/2.24
Time Ratio	t_R	$l_R^{1/2}$	1/2.24
Gravity Acceleration Ratio	g_R	–	1
Pressure Drop Ratio	ΔP_R	l_R	1/5
Flow rate Ratio	mf_R	$a_R \times l_R^{1/2}$	1/55.9
Power Ratio	q_R	$a_R \times l_R^{1/2}$	1/55.9

Overall scale ratio of the test facility is 1/125 for volume and 1/5 for length. The reactor power is simulated by electrical resistance heaters of 1.9MW capacity which corresponds to a 7 % of the scaled full power. Sodium was selected as the working fluid of the facility and its operating temperatures of the whole system were preserved to properly simulate natural circulation characteristics.

2.2 Scaling parameters of the PDRC system

The PDRC system includes the main pipe systems of the heat removal sodium loop and the heat exchangers connecting each heat transport path. Since the pipe arrangement of the PDRC system provides a natural circulation flow path of the loop sodium coolant, the pressure drop through the piping and the elevation difference between DHX and AHX were designed to satisfy the length scale of 1/5. The similarity of the sodium volume between the model and the prototype was also preserved to ensure a thermal effect of the scaled sodium inventory. The pipe arrangement of the scaled PDRC loop system is shown in **Fig.1**.

The heat exchangers such as DHX, AHX and IHX of the test facility were designed to preserve the overall heat transfer coefficient (U), the log-mean temperature differences (ΔT_{LMTD}). The scaling ratio of the pressure drop (ΔP), flow rate and heat capacity are also maintained as the given similarity criteria. All the scaled heat exchangers of the test facility have the same configurations and tube materials with the prototype, but the heat transfer tube diameters (ID/OD) were slightly adjusted in a scaling process to preserve the characteristics of heat transfer and pressure drop. The design parameters of the scaled heat exchangers are presented in **Table 2** and their schematic drawings are shown in **Fig.2**.

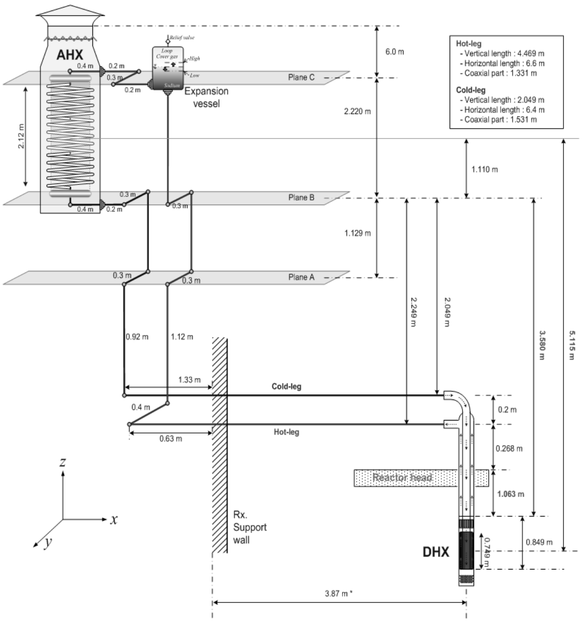
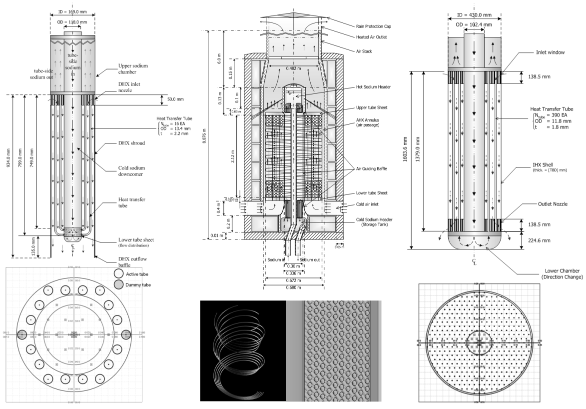


Fig.1 Configuration of the scaled PDRC loop system



(a) DHX (b) AHX (c) IHX

Fig.2 Schematics of scaled heat exchangers with the heat transfer arrangement

The major dimensionless numbers such as a Richardson number, friction number, modified Stanton number, time ratio number and a Biot number have been considered in the scaling process, and these were quantitatively evaluated to assess the scaling distortion for the scaled heat exchanger design. Based on the evaluation result, it was found that the dimensionless numbers representing the natural circulation of the sodium flow for DHX and IHX well satisfied the ideal scaling ratio within 10% for the Richardson number and about 30% for the modified Stanton number. In contrast, for air-side of the AHX, the distortion of a Richardson number, representing a balance between buoyancy force and viscous force, reaches 80% from the unity. This is mainly because there is much ambiguity to determine the hydraulic diameter of the shell-side AHX. To this end, it was found that the more reasonable scaling approach based on mathematical identity of analogous physical systems for naturally circulated air flow is necessary to reduce scaling distortions.

Table 2. Heat exchanger design parameters

Parameter		IHX			DHX			AHX			Ideal scale ratio
		Prototype [P]	Model [M]	Ratio [M/P]	Prototype [P]	Model [M]	Ratio [M/P]	Prototype [P]	Model [M]	Ratio [M/P]	
Heat transfer rate, Q (kWt)		380,900	6,814	0.018	8,250	148	0.018	8,250	148	0.018	0.018
U (W/m^2/K)		7855.88	8819.17	1.123	5664.76	5199.71	0.918	28.38	16.52	0.582	1.000
Heat transfer Area (m^2)		1252.56	19.94	0.016	25.66	0.5	0.019	1107.42	34.20	0.031	0.040
ΔT_{LMTD}(℃)		38.71	38.87	1.004	56.67	56.28	0.993	261.58	261.01	0.998	1.000
Tube length (m)		6.00	1.379	0.230	3.78	0.749	0.198	33.31	11.38	0.342	0.200
Tube bundle height (m)		6.00	1.379	0.230	3.78	0.749	0.198	5.91	2.12	0.359	-
Number of tubes (EA)		4188	390	0.093	90	16	0.178	196	40	0.204	-
Heat transfer Tube	ID (mm)	13.405	10.0	0.746	20	9.00	0.450	50.0	19.0	0.380	-
	OD (mm)	15.875	13.6	0.857	24	13.4	0.558	54.0	24.0	0.444	-
	thick. (mm)	1.235	1.8	1.457	2.0	2.2	1.100	2.0	2.5	1.250	-
Flowrate (kg/s)	tube-side	1450.175	25.94	0.018	44.73	0.800	0.018	44.73	0.800	0.018	0.018
	shell-side	1932.825	34.58	0.018	58.37	1.044	0.018	33.86	0.606	0.018	0.018
Velocity (m/s)	tube-side	2.919	1.439	0.493	1.826	0.907	0.497	0.134	0.081	0.604	0.446
	shell-side	0.937	0.441	0.471	0.359	0.153	0.426	6.175	2.769	0.448	0.446
Pressure drop (Pa)	tube-side	40590	8812.5	0.217	6630.4	1133.3	0.171	309.6	84.7	0.274	0.200
	shell-side	25730	4992.82	0.194	332.4	59.6	0.179	185.7	25.1	0.135	0.200
Richardson number	tube-side	-	-	0.946	-	-	0.803	-	-	0.932	1.000
	shell-side	-	-	1.038	-	-	1.091	-	-	1.784	1.000
Modified Stanton number	tube-side	-	-	0.614	-	-	0.813	-	-	1.202	1.000
	shell-side	-	-	0.475	-	-	0.638	-	-	1.114	1.000
Biot number	tube-side	-	-	1.173	-	-	1.008	-	-	1.014	1.000
	shell-side	-	-	1.054	-	-	0.843	-	-	0.774	1.000
Time ratio number	tube-side	-	-	0.219	-	-	0.330	-	-	0.360	1.000
	shell-side	-	-	0.230	-	-	0.384	-	-	0.512	1.000

3. Conclusions

The scaling analysis for the passive decay heat removal system design of the sodium thermal-hydraulic experimental facility (STEF) has been performed, and the key design parameters of the PDRC loop configuration and the major heat exchangers were reasonably obtained. The scaling distortion of the system components were also assessed by considering the major dimensionless numbers. Based on the assessment results, it was found that a more reasonable scaling approach for the air flow path needs to be considered in further works.

ACKNOWLEDGEMENT

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