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Development of Thermal-Hydraulic Analysis Model of an IHX in Modelica

Eui Kwang Kim *, Junkyu Han, Huee-Youl Ye, Jae-Hyuk Eoh
Korea Atomic Energy Research Institute, SFR NSSS System Design Division, 1045 Daedeok-daero,Yuseong-gu, Daejeon 305-353, KOREA
**Corresponding author: ekkim1@kaeri.re.kr*

1. Introduction

Dynamic Simulation is required for the design of the control system of thermal power plants. The use of the Modelica can offer a practical solution, allowing dynamic simulators that are detailed enough for the study of design, control strategy and operational requirements with limited computational requirements [1].

A thermal-hydraulic analysis model of an IHX is developed by using Dymola in the Modelica language. The Modelica model for IHX component will be used for the dynamic simulation modeling of the SFR nuclear plant. The model is validated through simulation of JOYO experiments [2]. The steady state of PGSFR IHX is analyzed by using the developed model. The steady state analysis results of the model are compared with design data [3]. Representative results of the model calculations are presented.

2. Methods and results

2.1 PGSFR IHX

The IHX transfers heat from the primary radioactive coolant to the secondary nonradioactive coolant while maintaining a physical separation between the two. Figure 1 shows PGSFR IHX design. Its configurations are (1) a cylindrical shell and tube, (2) vertical mounting, (3) single-wall tubes carrying secondary sodium in the tubes, (4) counter flow, (5) a baffled shell carrying primary sodium, (6) thermal expansion in tubes. The secondary system operates at a high pressure than the primary system to prevent leakage of radioactivity in case of a break in the IHX heat transfer surface.

2.2 Modeling of IHX

Simple model of a heat exchanger is modeled as two flow channels and one metal tube wall. Flow channels can be represented by the pipe elements [4], [5]. The primary fluid flows on the shell side in the PGSFR IHXs. For the primary and secondary side flow channels Dynamic pipe model with storage of mass and energy is built from models (Modelica.Fluid.Pipes.DynamicPipe) in the Modelica Standard Library.

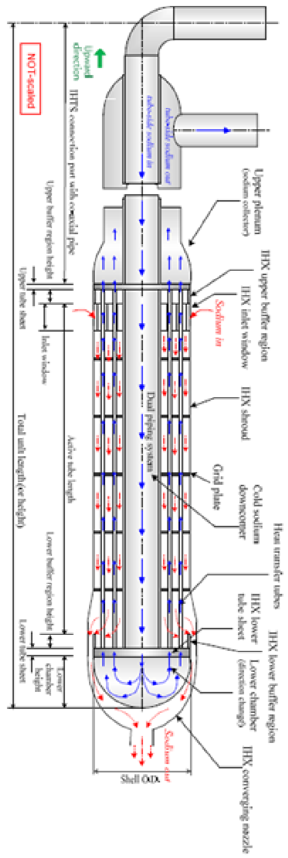

Fig. 1. PGSFR IHX.

The sodium liquid flows in flow channels. The Modelica Standard Library provides a number of medium models, but sodium properties of SolarTherm library [6] is used for the flow channels fluid. Pipe wall with capacitance (Modelica.Fluid.Examples. HeatExchanger.BaseClasses.WallConstProps) is also built from the Modelica Standard Library, it is assuming radially 1 dimensional heat conduction and constant material properties. The heat capacity, which is lumped at the center of the tube thickness, is accounted for, as well as the thermal resistance due to the finite heat conduction coefficient. Longitudinal heat conduction is neglected. The models of the IHX is presented in Fig. 2.

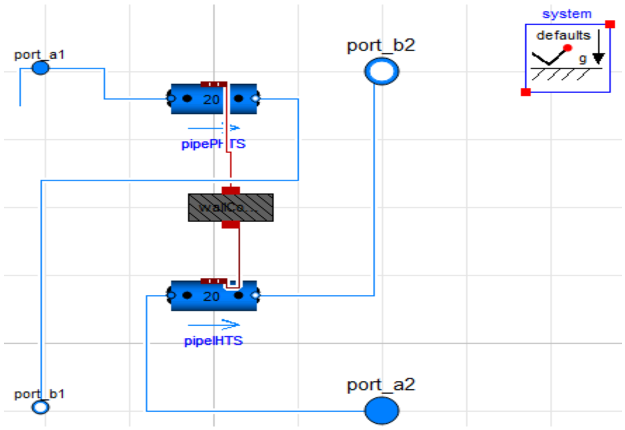

Fig.2. Modeling of the IHX.

2.3 Validation of IHX model

The model was validated with the results of the IHX hydrothermal test conducted by JOYO in Japan to verify the steady-state performance of the IHX model. JOYO is Japan's first SFR facility completed in 1977, with two IHXs and four sodium-air heat exchangers. The two IHXs are named IHX(A) and IHX(B), and each of the specifications is shown in Table 1. IHX(A) and IHX(B) are co-axial circular type and triangular type, respectively, and the shape and arrangement of the tubes are different.

Table 1. Specifications of JOYO IHX

Parameter	IHX(A)	IHX(B)
Tube Outer Diameter, mm	15.9	22.2
Tube Wall Thickness, mm	1.0	1.2
Tube length, mm	4000	4130.
No. of Tubes	2835	1812
Shell Inner Diameter, mm	493.0	393.4
Shell Outer Diameter, mm	1442.	1484.
Tube Arrangement	Co-axial circular	Tri-angular
Tube Pitch, mm	21.0	31.0
Eff. Heat Transfer Area, m^2	354	356
Effective Tube Length, mm	2500.	2817.
Material	STS 304	

The analysis was performed on the IHX(B), which is the triangular type applied to PGSFR IHX, and compared with the experimental results in Table 2.

The number of nodes applied is 30. The analysis showed that the relative error of the sodium outlet temperature on the shell side was within 0.3%, the relative error of the sodium outlet temperature on the tube side was within 0.4%, and the relative error of the heat transfer rate of case 1, case 2, and case 3 were well matched within 0.3%. The relative error of the heat transfer rate of case 4 and case 5 was slightly different from the experiment, and it was 6.5% and 4.5% (Table 3).

Table 2. Test Matrix of JOYO IHX

Parameter	Case				
	1	2	3	4	5
Shell inlet sod. temp. °C	393.8	393.1	400.3	374.9	403.0
Shell outlet sod. temp. °C	369.5	370.7	370.3	366.6	371.0
Shell side sod. flowrate, kg/s	302.9	302.3	303.6	304.4	303.8
Tube inlet sod. temp. °C	364.7	366.4	364.4	364.3	364.6
Tube outlet sod. temp. °C	388.0	387.7	393.1	372.7	395.4
Tube side sod. flowrate, kg/s	300.4	300.5	300.4	300.8	301.2
Heat Transferred, MW	9.44	8.68	11.68	3.24	11.93

Table 3. Comparison between Dymola Results and JOYO

		JOYO	results	Rel. error [%]
case1	Shell outlet [℃]	369.5	369.57	0.0
	Tube outlet [℃]	388	389.08	0.3
	Heat transfer [MW]	9.44	9.439	0.0
case2	Shell outlet [℃]	370.7	370.84	0.0
	Tube outlet [℃]	387.7	388.75	0.3
	Heat transfer [MW]	8.68	8.654	0.3
case3	Shell outlet [℃]	370.3	370.46	0.0
	Tube outlet [℃]	393.1	394.51	0.4
	Heat transfer [MW]	11.68	11.65	0.3
case4	Shell outlet [℃]	366.6	366.09	0.1
	Tube outlet [℃]	372.7	373.19	0.1
	Heat transfer [MW]	3.24	3.45	6.5
case5	Shell outlet [℃]	371	371.05	0.0
	Tube outlet [℃]	395.4	396.76	0.3
	Heat transfer [MW]	11.93	12.47	4.5

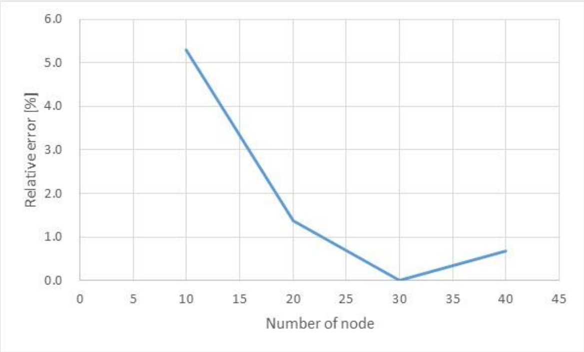

Fig.3. Relative error of the heat transfer rate in JOYO case1 (number of nodes : 10, 20, 30, 40)

Figure 3 shows the relative error of the heat transfer rate of JOYO case1 according to the number of nodes, and it seems best when it is 30.

2.4 Steady State Analysis of PGSFR IHX

The PGSFR IHX is a counter-flow, shell and tube type, vertical mounting heat exchanger. The design data is in Table 4.

In order to find out the node sensitivity, the heat transfer rate was compared by applying 10, 20, 30, and 40. Figure 4 compares the heat transfer rate according to the number of nodes, and it seems reasonable when there are 20 and 30. When it is 30, the relative error of the sodium outlet temperature and the heat transfer rate is 1% and 2.8% respectively. Figure 5 shows the sodium temperature distribution along the tube length at 100% power.

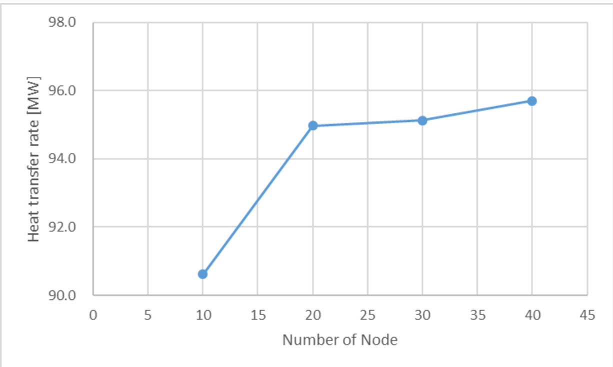

Fig.4. Heat transfer rate (number of nodes : 10, 20, 30, 40)

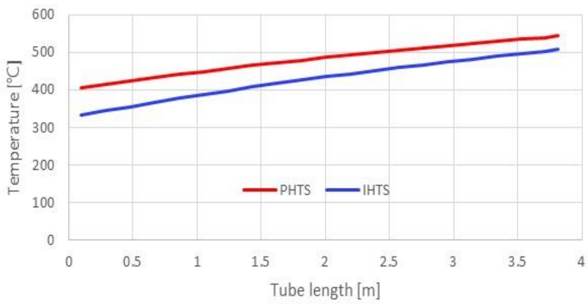

Fig. 5. IHX sodium temperatures at 100% power.

Table 4. Design data of PGSFR IHX

Design parameters		Design value
	No. of IHX	4
	Thermal duty per single IHX (MWt)	97.825
	No. of tubes	1512
	Pitch to Dia. (P/D)	1.50
	Tube OD (mm)	17.9
	Tube ID (mm)	15.5
	Thickness (mm)	1.2
	Tube material	9Cr-1Mo-V
	Active tube Length (Including 5% margin) (m)	3.8 (4.0)
	Thicknesses of upper / lower tubesheets (m) [3.1]	0.1 / 0.15
	Heights of upper / lower buffer regions (m)	0.3 / 0.3
	Total tube Length (m)	4.85
	Heat transfer surface area (m^2)	323.87
	No. of grid plates	5
	No. of flow holes on a grid plate	≥ 2640
	Diameter of the flow holes on the grid plates (mm)	8.5
	Curvature radius of the flow hole rounded edge (mm)	2
	IHX shell ID (m)	1.311
	Opening ratio of the inlet window	0.733
	LMTD (℃)	33.42
	UA total (kW/℃)	2941.65
Shell-side (Sodium)	Flow rate (kg/sec)	496.05
	Inlet temp. (℃)	545.0
	Outlet temp. (℃)	390.0
	Total pressure drop, ΔP_{total} (kPa)	12.7
	ΔP_{fric} at tube bundle (kPa)	1.4
	ΔP_{form} at grid plates (kPa)	7.2
	ΔP_{form} at inlet window (kPa)	0.06
	$\Delta P_{form+fric}$ at conversing nozzle (kPa)	4.0
Tube-side (Sodium)	Flow rate (kg/sec)	391.075
	Inlet temp. (℃)	332.3
	Outlet temp. (℃)	528.0
	ΔP_{total}, Total pressure drop (kPa)	12.5
	ΔP_{fric} at downcomer (kPa)	0.8
	ΔP_{form} at lower chamber (kPa)	5.3
	ΔP_{fric} within tubes (kPa)	6.4
	ΔP_{form} at upper plenum (kPa)	0.05

3. Conclusions

An analysis model of IHX based on the Modelica language was developed, and the performance of the model for the steady state was evaluated. As a result of analyzing the IHX hydrothermal test conducted by JOYO to verify the steady state performance, the sodium outlet temperature showed a good result with a relative error within 0.4%. PGSFR IHX was analyzed under 100% power. When 30 nodes were applied, the sodium outlet temperature and heat transfer amount were consistent with an accuracy within 1, 2.8% of the relative error compared to the design value.

The Modelica model for IHX component has been developed, and will be applied for the development of the dynamic simulation modeling of the SFR.

ACKNOWLEDGEMENT

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