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Computational Fluid Dynamics Simulation of an Intermediate Heat Exchanger in a Prototype Sodium-cooled Fast Reactor

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1. Introduction

In the development of the prototype Sodium-cooled Fast Reactor (SFR) in Korea Atomic Energy Research Institute (KAERI), thermal sizing and analyzing system codes had been written for the design of the sodium-to-sodium and sodium-to-air heat exchangers. The codes are going to be validated and verified by using experimental facilities.

One of the system codes is SHXSA (Sodium-to-sodium Heat Exchanger Sizing Analyzer) code [1]. The SHXSA code had been developed for the design of the Sodium-to-sodium Direct Heat Exchanger (DHX) and the Intermediate Heat Exchanger (IHX). The role of the IHX is to deliver the heat generated from the reactor core to the intermediate heat transport system (IHTS).

Four IHXs are installed in the primary heat transport system (PHTS). The IHX has a vertical orientation inside the reactor vessel, and its design arrangement properly provides downward and upward flow of the primary and the intermediate sodium, respectively. All IHXs are located above the reactor core assembly in the annular region between the reactor support barrel and the reactor baffle. In the 150MWe prototype SFR, each IHX unit is rated at 98.175MWt for a total rating of 392.7MWt [2], which is designed to be operated in a fully immersed condition inside the primary sodium pool.

As a preliminary work of the experiments, the Computational Fluid Dynamics (CFD) simulation has been conducted to show the fidelity and accuracy of the empirical correlations implemented in the SHXSA code. In the present work, the heat transport phenomena caused by the thermal fluid flow inside the IHX has been calculated via CFD simulation and its result is compared to that of the SHXSA code.

2. Methods and Results

2.1 Thermal Sizing System Code (SHXSA)

The IHX is a shell-and-tube type heat exchanger with straight tube bundle in which the two fluids flow in the opposite direction. The SHXSA code solves continuity, momentum, and energy equations for each control volume which is discretized in a simplified 1D domain. Various empirical correlations were implemented to calculate the heat transfer and the pressure drop of the shell-side and the tube-side. For the calculation of the convective heat coefficients, models of Lyon-Martinelli [3] and Schad-Modified [4] are used for the tube-side and the shell-side, respectively. Friction losses are calculated from Darcy friction factor [5] and form losses by geometric changes are obtained by the correlations presented in [6].

Primary sodium from the hot sodium pool enters the shell-side of the unit through the inlet nozzle and flows downward along the heat transfer tubes and five grid plates are installed for the tube support in the primary sodium flow path. The IHX consists of an upper and lower tubesheet separated by straight tubes with a central double-walled downcomer. The tube bundle of each IHX contains total 1,320 straight tubes of 15.9mm OD with 1.2mm wall thickness. All tubes are equally arranged on 23.8mm triangular pitches. Tube material is Mod. 9Cr-1Mo steel. Design parameters obtained from the SHXSA code are summarized in Table I.

Table I: Design parameters of the IHX

Active tube Length (m)	4.007
Heat transfer surface area (m^2)	264.2
No. of grid plates	5
IHX shell ID (m)	1.0559
LMTD (℃)	37.02
UA total (kW/℃)	2663.7

2.2 CFD Simulation

Thermohydraulic characteristics of the IHX encompass turbulent flow and conjugate heat transfer because of its geometrical complexity. Thus, the verification of the 1D system code is required to guarantee that the code is applicable to the multi-dimensional environment with complex physics. CFD is a useful tool for multi-dimensional flow analyses and system designs which can substantially reduce expense of experimental works. We utilized a renowned commercial CFD software, “STAR-CCM+ V7.04.011,” to analyze the flow physics in the thermal system of the IHX. Real geometry and operating conditions were adopted and the design from 1D code was assured in the viewpoint of system performance. Design requirement and parameters of heat exchanger obtained from conceptual design have been evaluated.

CATIA and ANSA were utilized to model the geometry and to generate the surface mesh, respectively. 1/4 symmetric part of IHX was modeled for simulation and the geometry model is shown in Fig. 1. Volume mesh was generated by polyhedral mesh and grid points near the solid boundaries were clustered by prism layer [7]. Embedded thin mesh was applied to generate solid mesh for the simulation of the heat conduction [7].

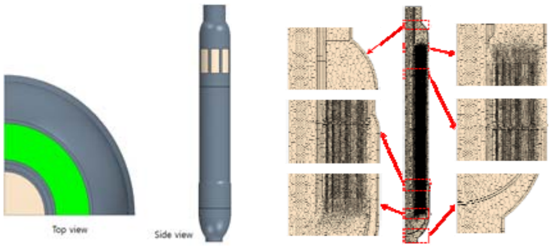

Fig. 1. IHX geometry (left) and mesh (right).

We calculated steady state problem with gravity effect and conjugate heat transfer through the solid structures. Radiation through the double-walled downcomer was solved by using the S2S model [7]. Material properties of sodium, argon, and solid are dependent on temperature. Standard κ-ε model with two-layer all y+ wall treatment was applied [7]. For the momentum and energy equations, the segregated model was used. Table II summarizes the boundary conditions.

Table II: Boundary conditions

Boundary	Condition
Inlet (Tube-side)	324.4℃, 378.98kg/s
Inlet (Shell-side)	545.0℃, 497.95kg/s
Double-walled downcomer	Radiation, No slip wall
Shroud outer surface in hot pool	545.0℃, No slip wall
Shroud outer surface in cold pool	390.0℃, No slip wall
Outlet (Tube-side)	Flow split outlet
Outlet (Shell-side)	Flow split outlet

In Table III, result from CFD is compared to that of the SHXSA code. The two results are in excellent agreement with each other. Temperature difference between the two is negligible. Temperature, pressure, and velocity distributions on a vertical section and a horizontal section are presented in Fig. 2. In the inlet and outlet regions of the shell-side, temperature is not equally distributed. Severe pressure loss occurs apparently in the inlet and grid plate regions.

Table III: Comparison of SHXSA and CFD

	Tube-side	Shell-side
Design condition (inlet)	324.4℃	545.0℃
SHXSA (outlet)	527.0℃	390.0℃
CFD (outlet)	528.1℃	389.3℃
Difference	+1.1℃	-0.7℃

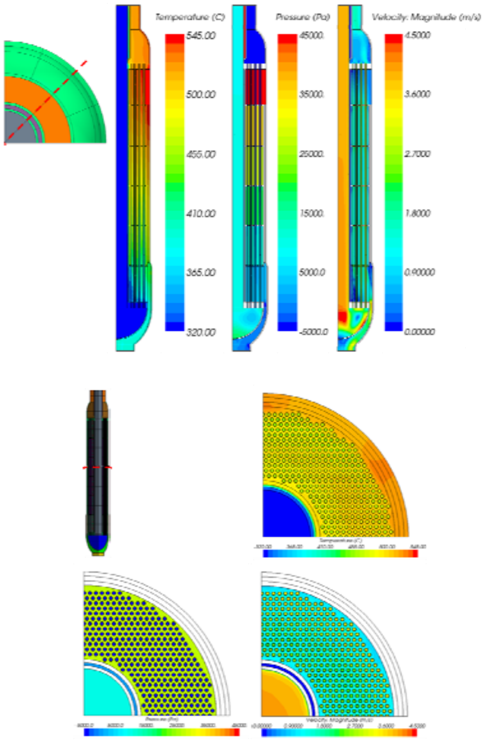

Fig. 2. Flow characteristics of vertical sections (top) and horizontal sections (bottom), respectively.

3. Conclusions

CFD simulation has been performed to validate the SHXSA code which is used for the IHX design and analysis. From the CFD result, it is verified that the SHXSA code can predict excellently the heat transfer phenomena in the IHX. Thus, the empirical correlations implemented in the SHXSA code can be considered to be very suitable for the analysis and design of the IHX in the development of the prototype SFR. The temperature and pressure distributions from the CFD simulation can be utilized for the improved design of the IHX.

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