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Numerical Analysis of Thermohydrodynamics Interfacing Supercritical Fluid and Liquid Metal

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1. Introduction

A shell-and-tube heat exchanger is the most common type of heat exchanger in nuclear power plants as well as oil refineries and other large chemical processes, and is suited for higher-pressure applications. This type of heat exchanger comprises a vessel with a bundle of tubes inside. One fluid runs through the tubes, and another fluid flows over the tubes through the shell to transport heat in-between. The tube bundle contains such varying tubes as plain, longitudinally finned, and so forth.

Heat exchangers may be divided into a shell-and-tube, double pipe, flat plate, helical coil or printed-circuit type according to geometry. The shell-and-tube heat exchanger is commonly adopted in a variety of power conversion systems. Tubular Exchanger Manufacturers Association (TEMA) categorized the shell-and-tube heat exchanger into a floating head, fixed tube sheet, U-tube and kettle type [1].

Maximization of the heat exchanger effectiveness tends to reduce the waste of energy, whereby increasing the efficiency of the nuclear power conversion system. A great deal of attempts has been made to improve efficiency of the heat exchanger by increasing the heat transfer surface area exposed to the working fluids and reducing the difference in temperature between the primary and secondary fluids. Limitations, though, exist to achievable tube densities based on manufacturing constraints and cooling requirements.

The shell-and-tube heat exchanger is definitively the most common type in nuclear power generation and is suited for higher pressure applications. This paper reports on a preliminary design work for a simplified counterflow heat exchanger called the Shell-and-tube Overall Layout Optimization (SOLO). Computational fluid dynamics (CFD) code CFX is applied to analysis of three-dimensional (3D) thermohydrodynamics in SOLO interfacing SCO_2 and liquid metal.

2. Heat Exchanger Design

The CFD analysis of shell-and-tube heat exchanger is complicated enough. Preliminary calculations are made for a simplified straight type (without any curves or baffles) shell-and-tube heat exchanger in which the phase changes in neither the primary nor the secondary coolant.

Conceptual design of SOLO has to do with counter flow shell-and-tube heat exchanger. The primary liquid metal flows on the shell side, while the secondary coolant SCO_2 flows on the tube side. The tubes are made of INCOLOY Alloy 800 with higher thermal and corrosion resistance. Table 1 contains typical design parameters for SOLO.

Table 1. Design parameters of SOLO

General	
Primary / Secondary Coolant	Pb / SCO_2
Tube Material	INCOLOY Alloy 800
Tube Length / Diameter / Thickness [m]	1 / 0.016 / 0.002
Tube Arrangement	Equilateral Triangular
Operating Condition	
Primary / Secondary Coolant Mass Flow Rate [kg/s]	1276.32 / 112.8
Primary / Secondary Coolant Inlet Temperature [ºC]	560 / 390
Primary / Secondary Coolant Pressure [MPa]	0.101326 / 19.90

3. Computational Analysis

The primary coolant properties are obtained using respective equations with temperature in K [2]. The coolant mean temperature between the core inlet and outlet is taken as 480ºC.

Density:

$$r_{Pb}[kg/m^3] = 11367 - 1.1944 \cdot T \quad (1)$$

Specific heat capacity:

$$c_p[J/kg\cdot K] = 175.1 - 4.961\times10^{-2}\cdot T + 1.985\times10^{-5}\cdot T - 2.099\times10^{-9}\cdot T^3 - 1.524\times10^{6}\cdot T^{-2} \quad (2)$$

Viscosity:

$$h_{pb}[Pa\cdot s] = 4.55\times10^{-4}\cdot \exp\left(1069/T\right) \quad (3)$$

Thermal conductivity:

$$l_{pb}[W/m\cdot K] = 9.2 + 0.011\cdot T \quad (4)$$

The CATIA generated 3D heat exchanger channel model in Fig. 1. with tubes and coolants is exported to the ANSYS Workbench geometry, which then is applied to CFX. The sweep method is applied to the tube part in view of less importance than the coolant part. The primary and secondary coolants are dealt with by CFX with more fine meshes of 128,022 nodes and 498,179 elements.

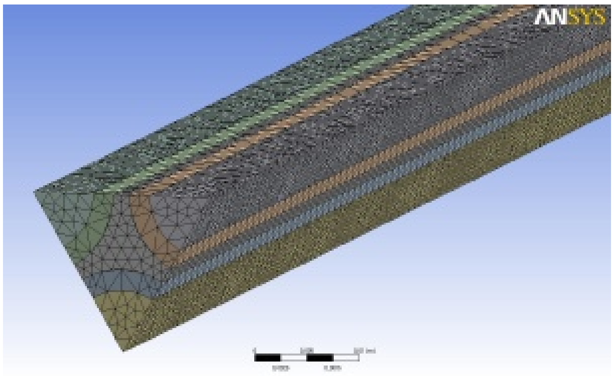

Fig. 1. Heat exchanger analysis model and meshes

The reference pressure was set to reduce the truncation error in the secondary section. The buoyancy effect was excluded for simplified calculation. The shear stress transport model was chosen as a turbulence model. The inlet, outlet and symmetry boundary conditions for each section are applied.

4. Result

Heat transfer is calculated from the primary to secondary fluid through the tube. Thus the primary fluid is cooled while the secondary fluid is heated gradually. Table 2 presents the inlet and outlet temperature in the primary and secondary sections.

Table 2. Inlet and outlet temperature

	Inlet Temperature	Outlet Temperature
Primary [K]	833.1	721.1
Secondary1 [K]	663.2	713.5
Secondary2 [K]	663.2	713.2
Secondary3 [K]	663.2	713.1

Fig. 2. shows the linear temperature variation in the primary and secondary sections. The efficiency of the SOLO heat exchanger is calculated [3, 4] to be 29.5 %.

5. Conclusions

The preliminary calculational results indicate that the temperature need at least be 492 ºC in the secondary coolant outlet to obtain a 60% efficient SOLO heat exchanger by changing several design parameters. First and foremost, the tube thickness has to be decreased so as to reduce thermal resistance by conduction in the solid. The tube is 2 mm thick in the current design. The tube thickness shall be optimized to ensure not just high heat transfer through but low risk of tube rupture. Second, tube material has to be designed to increase the thermal conductivity as well as the corrosion and abrasion resistance under the high pressure and temperature condition. Third, the primary and secondary fluid flow rates ought to be controlled to increase contact time with the solid material.

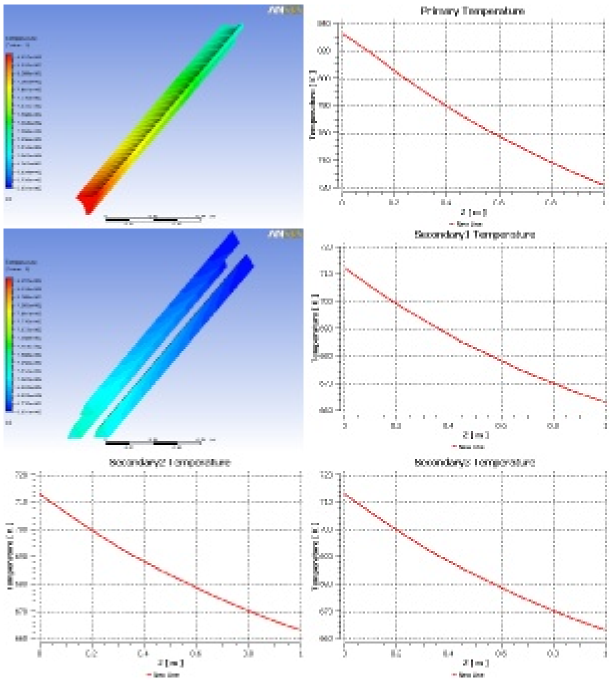

Fig. 2. Primary and secondary section temperature

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