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Development of a 1D thermal-hydraulic analysis code for once-through steam generator in SMRs using straight tubes

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1. Introduction

Diverse integral/small-modular reactors (SMRs) have been developed [1~5]. Once-through steam generator (OTSG) which generates superheated steam without steam separator and dryer [3] was used in the SMRs to reduce volume of steam generator. It would be possible to design a new steam generator with best estimate thermal-hydraulic codes such as RELAP [6] and MARS [7]. However, it is not convenience to use the general purpose thermal-hydraulic analysis code to design a specific component of nuclear power plants [8]. A widely used simulation tool for thermal-hydraulic analysis of drum-type steam generators is ATHOS [9], which allows 3D analysis. On the other hand, a simple 1D thermal-hydraulic analysis code might be accurate enough for the conceptual design of OTSG.

In this study, thermal-hydraulic analysis code for conceptual design of OTSG was developed using 1D homogeneous equilibrium model (HEM). A benchmark calculation was also conducted to verify and validate the prediction accuracy of the developed code by comparing with the analysis results with MARS. Finally, conceptual design of OTSG was conducted by the developed code.

2. Development of 1D thermal-hydraulic code for OTSG

In this study, 1D HEM was used to simple analyze two-phase flow heat transfer. The HEM has following assumptions.

- Uniform velocity between gas and liquid phase
  $(u_g = u_f = u)$ (1)
- Uniform temperature between gas and liquid phase
  $(T_g = T_f = T)$ (2)
- Uniform pressure between gas and liquid phase
  $(P_g = P_f = P)$ (3)

The axial heat conduction in the tube wall was neglected.

2.1 Governing equations

Conservation equations for mass, energy, and momentum for primary and secondary sides of OTSG are as follows.

- Mass

$$\dot{m} = \bar{\rho} u A = \text{Constant} \quad (A = \text{constant}) \tag{4}$$

- Momentum

$$(-\frac{\mathrm{dP}}{\mathrm{dz}}) = -[(\frac{\mathrm{dP}}{\mathrm{dz}})_F + (\frac{\mathrm{dP}}{\mathrm{dz}})_A + (\frac{\mathrm{dP}}{\mathrm{dz}})_G] \tag{5}$$

$$-(\frac{\mathrm{dP}}{\mathrm{dz}})_F = \frac{2}{D_H} f_{TP} \frac{G^2}{\bar{\rho}} \tag{6}$$

$$-(\frac{\mathrm{dP}}{\mathrm{dz}})_A = G^2 \upsilon_{fg} \frac{dx}{dz} \tag{7}$$

$$-(\frac{\mathrm{dP}}{\mathrm{dz}})_G = \bar{\rho} g \sin\theta \tag{8}$$

- Energy

$$Q = q'' p_h = \dot{m} \frac{di}{dz} = \dot{m} i_{fg} \frac{dx_e}{dz} \tag{9}$$

2.2 Heat transfer and friction correlations

Table 1 shows a summary of correlations used to calculate heat transfer coefficient and friction factor of primary and secondary sides of OTSG. Two different correlations were used to estimate friction factor for single phase (Petucov [10]) and two phase flow (McAdams [11])

Table 1. Correlations for heat transfer coefficient and friction factor

Region	Primary side	Secondary side
Superheated	Gnielinski [12]	Gnielinski [12]
Two-phase		Chen [13]
Subcooled		Gnielinski [12]
Friction factor	Petucov [10] McAdams [11]	

The overall heat transfer coefficient and heat transfer area are given as follows,

$$\frac{1}{U} = \frac{1}{h_{1st}} \frac{D_O}{D_i} + \frac{D_O}{2k_{tube}} \ln \frac{D_O}{D_i} + \frac{1}{h_{2nd}} \tag{10}$$

$$A = \pi D_o L \times \text{No.tube} = \frac{Q_{total}}{U \Delta T_{lm}} \times \text{margin} \tag{11}$$

2.3 Algorithm

Fig. 1 shows the calculation algorithm of the developed code.

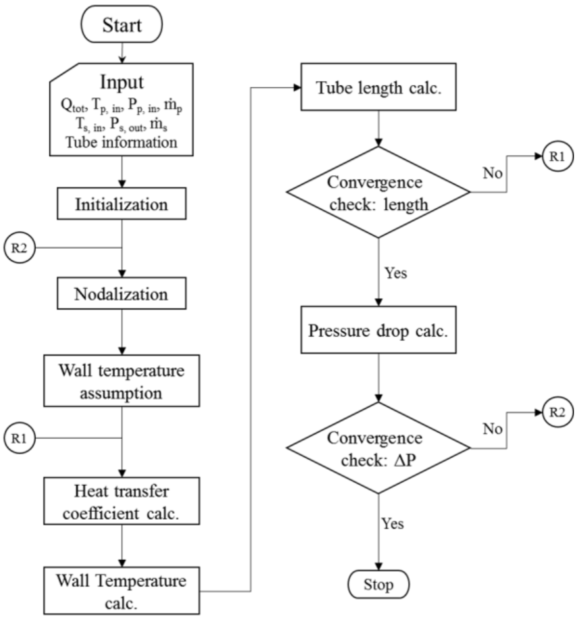

Fig. 1. Calculation algorithm of the developed code

3. Benchmark calculation

To verify and validate the developed code, the design and analysis results for the OTSG by Babcock & Wilcox (B&W) company [14] were chosen. Table 2 summaries the data for the B&W OTSG.

Table 2. Design specification of B&W OTSG

Parameters	Value	
Thermal power (MW_{th})	1284	
Number of tubes	15531	
Tube length (m)	15.96	
Tube O.D. (mm)	15.875	
Tube thickness (mm)	0.864	
Tube pitch (mm)	22.225	
	Primary	Secondary
Inlet Temp. ($^{\circ}C$)	317.7	237.8
Outlet Temp. ($^{\circ}C$)	290.0	312.8
Pressure (bar)	151.7	63.8
Mass flow rate (kg/s)	8273.2	680.4
Superheating ($^{\circ}C$)	-	33.2

Figs. 2-5 show comparisons of the analysis results by the developed code and MARS. It is found that there are reasonable agreements in fluid/wall temperature and secondary pressure distribution. However, heat transfer coefficient in the secondary side has a considerable difference for high quality ($x \geq 0.8 \sim 0.9$) as the developed code did not consider effects of flow regime. However, the difference in heat transfer coefficient made an error less than 5% in total tube length.

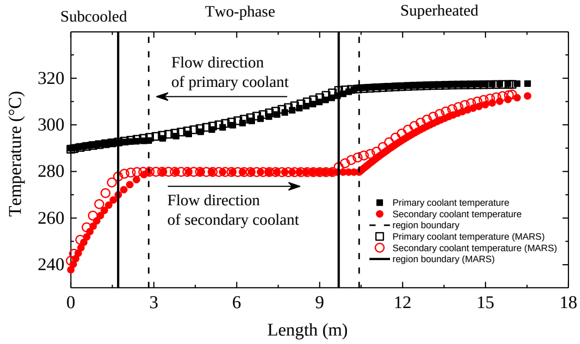

Fig. 2. Axial distribution of the primary and secondary side fluid temperature

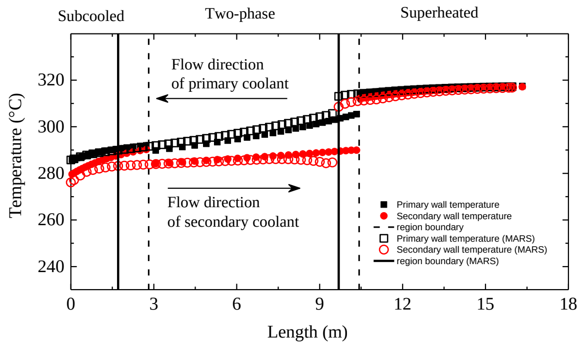

Fig. 3. Axial distribution of the primary and secondary side wall temperature

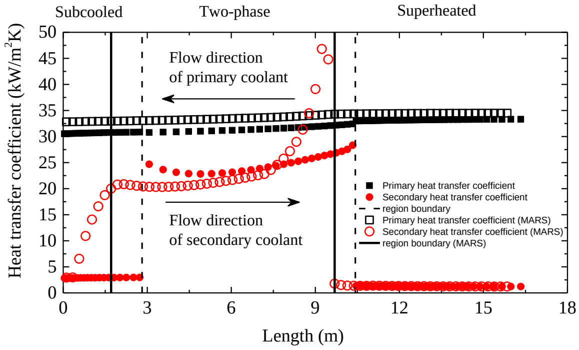

Fig. 4. Axial distribution of the primary and secondary side heat transfer coefficient

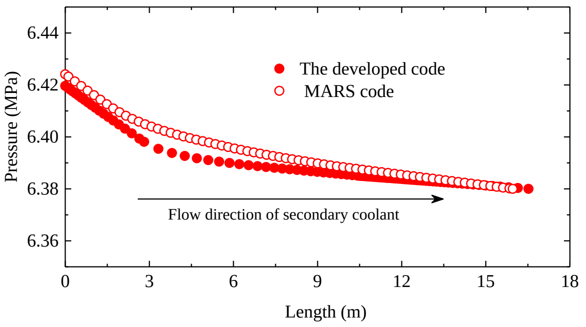

Fig. 5. Axial pressure distribution in the secondary side

4. Conceptual design

For the integral type SMRs, volume of steam generator is strongly affected by exit conditions of steam. Therefore, conceptual design of new OTSGs for integral type SMRs was tried using the developed code. Table 3 shows the input parameters for the imaginary OTSG.

Table 3. Input parameters for an imaginary OTSG

Parameters	Value	
Thermal power (MW_{th})	800	
Tube length (m)	7.62	
Tube O.D. (mm)	15.875	
Tube thickness (mm)	0.864	
Tube pitch (mm)	22.225	
	Primary	Secondary
Inlet Temp. ($^{\circ}C$)	325.7	260.9
Pressure (bar)	155	63.8
Mass flow rate (kg/s)	8273.2	680.4
Superheating ($^{\circ}C$)	-	33.2
Circulation ratio	-	2.59

Table 4. Calculation results for an imaginary OTSG

Parameters	Superheating	Recirculation
Volume of SG (m^3)	58.56	34.75
Effective height of SG (m)	12.84	7.62
Heat transfer area (m^2)	6889.4	4088.6
Secondary exit condition	$\Delta T_{sup} = 37.9^{\circ}C$	$x_{out} = 0.385$

Two types of OTSG with superheating or recirculation were analyzed as shown in Fig. 6. Table 4 shows the result of conceptual design of superheating and recirculation type OTSGs. It was found that volume of the recirculation type OTSG was smaller than the superheating type one. Therefore, the recirculation type OTSG has an advantage in reducing the total volume of SMRs.

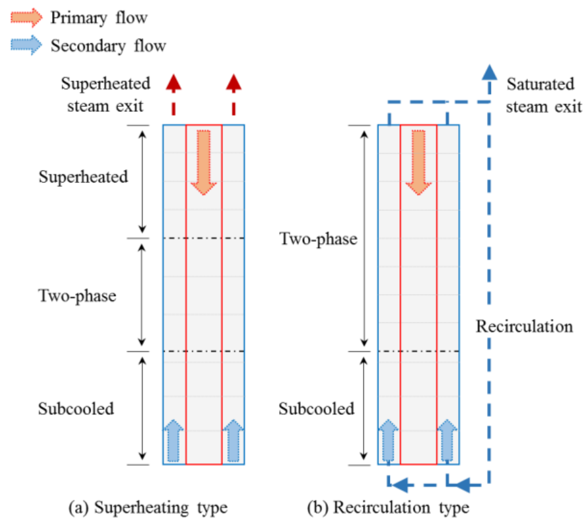

Fig. 6. Schematic diagram for two- types of imaginary OTSG: (a) Superheating type, (b) Recirculation type

5. Conclusions

A simple 1D thermal-hydraulic analysis code was developed for the purpose of conceptual design OTSG for SMRs. A set of benchmark calculations was conducted to verify and validate the analysis accuracy of the developed code by comparing results obtained with a best-estimated thermal-hydraulic analysis code, MARS. Finally, analysis of two different OTSG design concepts with superheating and recirculation was demonstrated using the developed code.

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