A computer code for the thermal-hydraulic analysis of a helical-coil-type once through steam generator

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Abstract: **A** helical-coil-type once through steam generators (HOTSG) are considered as the first choice for its advantages in compactness and increasing of heat transfer in Small Modular Reactor (SMR). In this study, a mathematical models of void fraction, pressure drop, and heat transfer for different boiling flow conditions in a helical coil tube were presented and a computer code (OTSG-TH）for thermal-hydraulic analysis of the HOTSG was developed. Firstly, calculations were carefully validated and verified with steady-state results of ONCESG (Once Through Steam Generator) code and MRX (Marine Reactor X) experiment. The code was used for thermal hydraulic analyses and geometric design of a HOTSG. A postulated scenario of loss of feed water, was also analyzed in this study. It has showed that the OTSG-TH code can be successfully used for steady and transient state analyses of a HOTSG.

Keyword: OTSG; helical-coil-tube; two-fluid model; thermal-hydraulic

1 Introduction

Options of the primary heat transport loop heat exchangers for the SMR are currently evaluated. A helical-coil-type Steam Generators are widely used in SMR for their advantages in compactness and increased heat transfer efficiency [1]. The curvature of the pipe can cause centrifugal force, which induce the secondary flow, results in significantly larger heat transfer and friction factors than straight pipes. Therefore, HOTSG is currently considered as the forefront of steam generator technology due to the heat transfer efficiency up to 43% higher than that of a straight tube OTSG [2].

Yoon *et al.* [3] developed the ONCESG code for HOTSG that can calculate the characteristics of heat transfer area, pressure and temperature. Hoffer *et al.*[2] modeled a helical-coil steam generator with Relap5-3D, in particular, the response of the steam generator primary and secondary systems to the exponential decrease of primary pressure was reported. Cioncolini *et al.*[4], assessed the main computational challenges of the thermal hydraulic analysis of International Reactor Innovative and Secure (IRIS) steam generator and obtained steady state thermal parameters. Yuan[5] programmed the Thermal Hydraulic performance analysis code of HOTSG by C# and evaluated according to the data of the IRIS at steady and transient states.

The most prominent characteristic of a helically coiled tube is the uneven heat flow mixing induced by arrangement of bundles, which may result unstable flow occurrence. Most of the research adopted the homogeneous flow model in Two-Phase slug flow and take some simplification, which may not really reflect the heat transfer of HOTSG. In this study, a mathematical model of HOTSG is developed by two-fluid model, and found a complete thermal transition model for heat, mass and momentum transfer between vapor and liquid phases. Scope of this paper is to address the thermal hydraulic analysis of the HOTSG, in order to select the computing tools necessary for the analysis and to highlight the corresponding modeling and numerical concerns to be address. A computer code of the thermal hydraulic analysis of HOTSG is developed. To benchmark the OTSG-TH code, the designed parameters of MRX as well as SMART steam generator are calculated. In addition, a transient

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state, flow rate step changes in secondary side, was also analyzed in this study.

2 Models and methodology

In the helical coiled tube once through generator, single phase primary coolant flows outside down the helical coil tubes. Steam generators typically transfer heat from the shell side coolant to the tube side coolant, producing steam within the tubes. In this study, the helical coiled bundle of tubes is modeled as a single tube with equivalent both flow and heat transfer surface areas, hydraulic diameter and heated hydraulic diameter. The primary and secondary systems of model are divided into several control volume. Fig.1

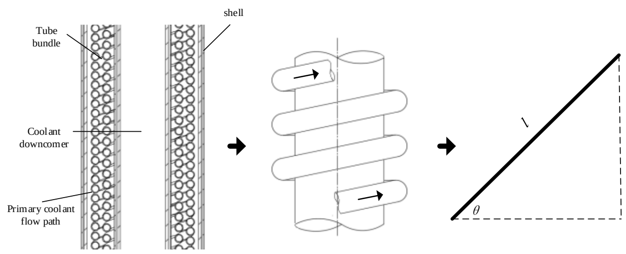

Fig.1 Simplifying assumption of HOTSG.

2.1 Governing equations

Two-Fluid model treats the vapor and liquid phases as separate fluid which is assumed that there is a moving vapor-liquid interface between two phases. Considering heat, mass and momentum transfer, each phase contacts with wall surface. In addition, following assumptions are made for physical model of HOTSG.

(1) No phase transition in shell side
(2) No heat conduction in the tube axial direction
(3) Ignore the energy dissipation caused by Reynolds Stress
(4) Equal pressure between vapor and liquid phases and no heat conduction due to temperature difference
(5) No mass, energy and momentum storage on the interface
(6) No reverse flow of either primary and secondary flow.

Conservation equations for mass, energy and momentum are used for the primary and secondary sides.

Mass conservation equation

$$\frac{\partial(\alpha_g \rho_g)}{\partial t} + \nabla \cdot (\alpha_g \rho_g u_g) = \Gamma_g \tag{1}$$

$$\frac{\partial(\alpha_l \rho_l)}{\partial t} + \nabla \cdot (\alpha_l \rho_l u_l) = \Gamma_l \tag{2}$$

Momentum equation

$$\begin{aligned}&\frac{\partial\left(\alpha_l \rho_l u_l\right)}{\partial t} + \nabla \cdot \left(\alpha_l \rho_l u_l u_l\right) = \\ &-\alpha_l \frac{dp}{dx} - \alpha_l \rho_l g \cos\theta + F_{wl} + F_{gl} + \Gamma_l u_{li}\end{aligned} \tag{3}$$

$$\begin{aligned}&\frac{\partial\left(\alpha_g \rho_g u_g\right)}{\partial t} + \nabla \cdot \left(\alpha_g \rho_g u_g u_g\right) = \\ &-\alpha_g \frac{dp}{dx} - \alpha_g \rho_g g \cos\theta + F_{wg} + F_{lg} + \Gamma_g u_{gi}\end{aligned} \tag{4}$$

Energy equation

$$\begin{aligned}&\alpha_l \rho_l \frac{\partial\left(h_l\right)}{\partial t} + \left(\alpha_l \rho_l u_l\right) \cdot \nabla h_l = \\ &-\alpha_l \left(\frac{\partial p}{\partial t} + u_l \nabla p\right) + Q_{wl} + \Gamma_l \left(h_g^s - h_l\right) \\ &+\Gamma_l \left[\left(h_{li} + \frac{1}{2}\left(u_{li}^2 - u_l^2\right)\right)\right]\end{aligned} \tag{5}$$

$$\begin{aligned}&\alpha_g \rho_g \frac{\partial\left(h_g\right)}{\partial t} + \left(\alpha_g \rho_g u_g\right) \cdot \nabla h_g = \\ &-\alpha_g \left(\frac{\partial p}{\partial t} + u_g \nabla p\right) + Q_{wg} + \Gamma_g \left(h_g^s - h_g\right) \\ &+\Gamma_g \left[\left(h_{gi} + \frac{1}{2}\left(u_{gi}^2 - u_g^2\right)\right)\right]\end{aligned} \tag{6}$$

2.2 Hydraulic model

In the steam generator circulation channel, pressure drop is calculated as follows:

$$\Delta P = \Delta P_f + \Delta P_{el} + \Delta P_a + \Delta P_{loc} \tag{7}$$

Where, ΔP_f is the friction drop; ΔP_{el} is the gravitation drop; ΔP_a is the acceleration drop; ΔP_{loc} is the local pressure drop.

The local drop is low in helical coil tube, that means we can only consider the friction, acceleration and gravitation drops. In a typical HOTSG, the coolant in the primary side flows upward, whereas the coolant in the secondary side flows downward. Therefore, the gravitational pressure drop in the primary side is negative whereas that in the secondary side is positive.

Respectively, the friction factor of friction drop is calculated by using Chexal-Harrison[6] correlation for the tube side and Yin[7] correlation for the shell side of the helical coils.

2.3 Heat transfer correlations

The flow patterns are divided into six regimes: single liquid phase, subcooled boiling, saturated boiling, transition boiling, film boiling and single-phase steam respectively. To judge the heat transfer conditions, it needs to determine demarcation points for each operating condition and then adopt correct structural correlations. Onset of the nucleates(ONB) is used by Saha-Zuber correlation[8]. Furthermore, Dry-out point is employed by Biasi correlation[9]. The empirical correlations are summarized in Table 1.

Table 1 Empirical correlations for heat transfer coefficients

Pattern Judging	Heat transfer area	Empirical correlation
$T_w < T_{FDB}$	Single-Phase water	Mori-Nakayama[10]
$T_s < T_{sat}$	Subcooled boiling	Chen[11]
$T_W < T_{CHF}$	Saturated boiling	Chen
$T_W < T_{MFB}$	Transition boiling	Berenson[12]
$T_W > T_{MFB}$	Film boiling	Miropolskii [13]
$0.9999 \le \alpha$	Single-Phase vapor	Mori-Nakayama

Since the helical tube inclination angle is small, the primary side coolant flow pattern is similar to cross tube bundles. The heat transfer in the shell side is used by Zukauskas[14] correlation, eqn. (8), which is widely used to calculated heat transfer coefficient of coolant swept outer tube. This correlation is reported by the heat transfer data of a circular tube in the crossflow with viscous fluids and gases.

$$Nu = C\,\mathrm{Re}^m\,\mathrm{Pr}^{0.33}\left(\frac{\mathrm{Pr}}{\mathrm{Pr}_w}\right)^{0.25}\varepsilon_n \qquad (8)$$

Where, Nu, Re and Pr are Nusselt, Reynolds, and Prandtl numbers respectively. ε_n is the tube row correction factor.

Aligned tube bundle,
C=0.235, m=0.65;
Staggered tube bundle,
C=0.415, m=0.60.

2.4 Solution Method

Two-phase flow in the helical tube is solved by using the SIMPLE arithmetic. The iteration scheme is as follows:

(1) Assume a velocity field and pressure field, marked as (u^0, p^0);
(2) Solve coefficients and sources of momentum discrete equations, obtain u^*;
(3) Solve the pressure correction equation and get the pressure correction value p;
(4) Correct speed and pressure based on pressure corrections, obtain (u^1, p^1);
(5) Use the corrected number and pressure (u^1, p^1) as solutions to this iteration layer.

Pressure and velocity correlation equations of two-phases flow in the helical tube are solved by using the SIMPLE arithmetic. There are two iterative processes of the program, the inner and outer iteration, which are solved by Sor iteration in this study. By using finite volume method, the control equations are solved via coupling the interaction force between liquid and gas phases. The diffusion terms were solved by central differencing, in addition, the convection terms were dealt with by second-order upwind scheme. Besides, vapor and liquid phases are used different relaxation factors in two -phases flow, generally, to obtain a convergent solution. Fig.2 shows the flow chart of the OTSG-TH code.

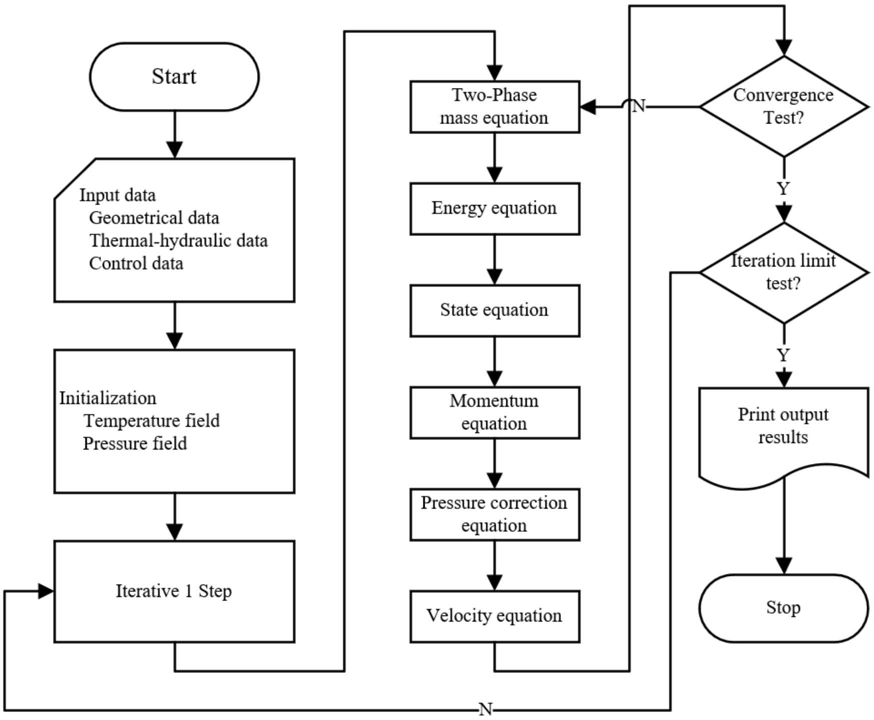

Fig.2 Flow chart of OTSG-TH.

3 Results and discussions

3.1 Validation and verification

Table 2 Data for MRX & SMART steam generator design

System parameters	MRX	SMART
Number of tubes	388	324
Tube material	Inconel-800	Titanium
Tube inner/outer diameter (mm)	14.8/19	9/12
Pitch (mm)	25/25	17/13
Innermost coil diameter (m)	2.095	0.182
Outermost coil diameter (m)	3.295	0.726
Rated power (MW)	100	28.25
Primary coolant flow (kg/s)	1250	128.3
Secondary coolant flow (kg/s)	46.67	12.7
Primary & Secondary pressure (MPa)	12/4	15.5/3.4
Primary inlet temperature (°C)	292.5	310
Secondary inlet temperature (°C)	185	180

To verify the correctness of the program, the calculations were carefully validated and verified with steady-state results of ONCESG (Once Through Steam Generator) code and designed data. Then, the code was used for thermal hydraulic analysis and geometric design of a HOTSG. Overall characteristics, such as void fraction, fluid and wall temperature, pressure drop, and heat flux are discussed. In addition, the SMART steam generator thermal hydraulic parameters were carefully calculated by OTSG-TH, and showed well agreement with ONCESG results.

3.1.1 Results of the once-through steam generator of the MRX

The MRX is a JAERI (Japan Atomic Energy Research Institute) developed integral reactor of 100MWt capacity for ship-mounted applications. The MRX, an integrated nuclear reactor, utilized a helical-coil-type once through steam generator. The steam generator has 388 tubes wound between the Core Support Barrel (CSB) and Reactor Pressure Vessel (RPV). The heat transfer tubes are made by Incoloy-800, arranged into 25 coil columns. Each coil column has a different number of tubes to make the length of each tube similar. The design data of the MRX steam generator, ONCESG results and OTSG-TH calculated results are summarized in Table 2. The thermal hydraulic parameters, such as temperature, pressure drop, heat flux and void fraction calculated by OTSG-TH are compared with experiment and ONCESG results, which shows a good degree of matching. However, the secondary side pressure is calculated by Chexal-Harrison model, which are widely used in the straight tubes, ignored the increasing pressure drop caused by secondary flow. The pressure drop model will be revised for further works.

Table 3 OTSG-TH simulation results for MRX steam generator

Output parameters	MRX	ONCESG	OTSG-TH
Primary outlet temperature (°C)	282.5	282.5	281.2
Secondary outlet temperature (°C)	289	289	291.8
Heat transfer area (m^2, inside)	754	672.5~728.1	728.8
Axial height(m)	2.1	1.71~1.85	1.85
Average tube length(m)	-	37.3~40.4	40.4
Shell-side pressure drop (MPa)	0.9E-2	1.2E-2	1.39E-2
Tube-side pressure drop (MPa)	0.64	0.45~0.49	0.36

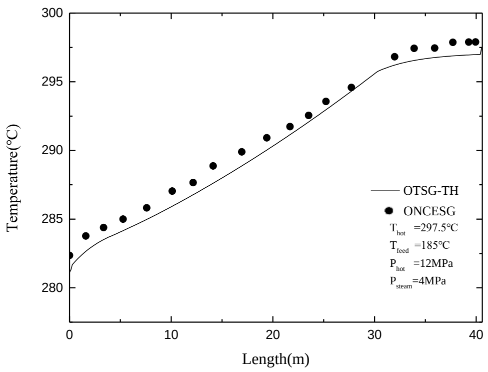

Fig.3 OTSG-TH calculated primary side temperature and comparison with ONCESG calculations.

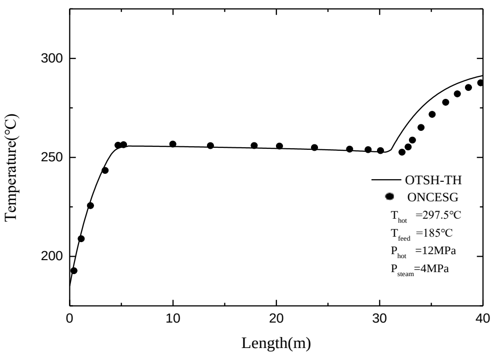

Fig.4 OTSG-TH calculated secondary side temperature and comparison with ONCESG calculations.

Figure 3 shows the primary coolant temperature calculated by OTSG-TH. The overall coolant temperature profiles agree well with ONCESG calculated results. Also, as it can be seen in Table 3, the inlet and the outlet coolant temperatures of primary side agreed exactly. The outlet coolant temperature of primary side is 281.2 **°C**, slightly lower than the design parameter, with an error of only 1.3 **°C**.

Figure 4 shows that the OTSG-TH calculated secondary coolant temperature. The flow along the tube length are divided into six heat transfer regimes: Single-phase, subcooled boiling, saturated boiling, transition boiling, film boiling and vapor. As we can be seen in Fig.4 and table 3, the curve agrees well with the design data of the MRX and ONCESG results. The secondary side outlet temperature is just 2.8 **°C** higher than ONCESG results.

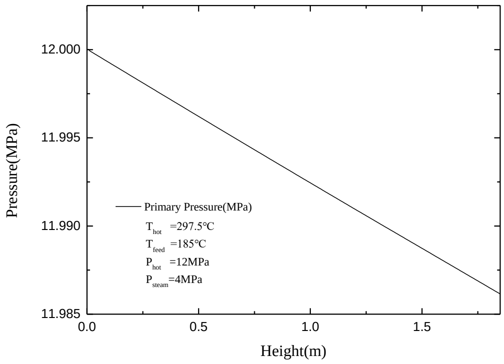

Fig.5 OTSG-TH calculated primary side pressure.

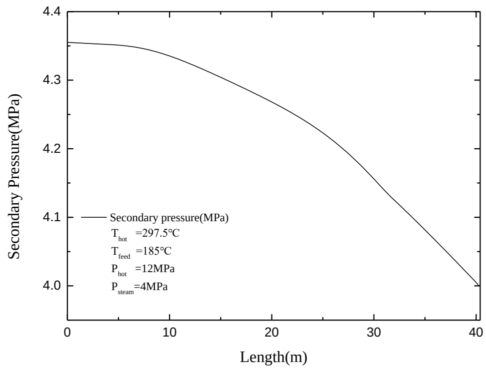

Fig.6 OTSG-TH calculated secondary side pressure.

The gravitational pressure drop in the primary side is negative whereas that in the secondary side is positive, causes the primary side pressure drop is very low. Figure 5 and 6 show the pressure calculated by OTSG-

TH of the primary and secondary sides. Secondary side coolant flows in the helical tube, the flow direction is changing, causes the route loss increased. In addition, vortex and secondary circulation intensify flow loss. When the secondary side fluid is at single phase water region, there's no bubble generation, and we can see that the friction resistance grows slightly. After ONB, bubble generation rate and flow velocity increase, cause the secondary pressure drops faster. However, there's no phase change in the primary side, so that the primary pressure can maintain a certain change trend and the pressure drop is small. What's more, the secondary side coolant flow velocity changes so fast, which means, the pressure drop is large. Conversely, the flow velocity of primary side changes little or increases slightly, therefore, the pressure drop, especially friction drop is significantly less than the secondary side.

3.1.2 Results of the Once-through Steam Generator of the SMART

SMART is a small modular reactor designed by KAERI (Korea Atomic Energy Research Institute) that generates a rated thermal power of 330MWt. The steam generator component is of the once-through, helically coiled tube type. The results calculated by OTSG-TH code agree well with the SMART design data and with the results calculated using the ONCESG code. Compared to the design data, the thermal hydraulic parameters are overestimated less than 5%. The design data of the SMART steam generator and OTSG-TH code calculations are listed in Table 4.

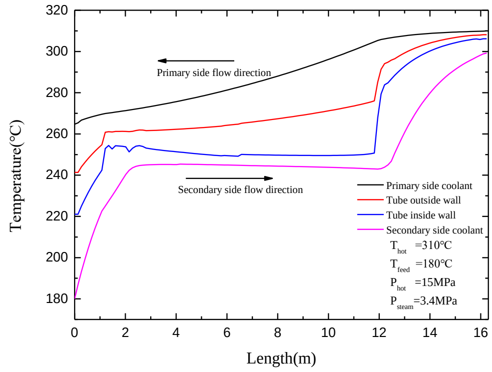

Fig.7 Temperature distributions of SMART SG.

Figure 7 shows the calculated temperature profiles of primary and secondary coolants including the temperature distributions on both inside and outside tube surfaces. Also, the inlet and outlet coolant temperatures of both primary and secondary sides agreed. The temperature of the secondary side rises fast to the saturated temperature and then decreases slightly because of pressure drop. The temperature of the wall varies because of different heat transfer coefficients in different positions. After dry-out point, there is an abrupt temperature rises in the secondary side at that position, and finally, the water becomes superheated vapor.

Table 4 OTSG-TH simulation results for SMART steam generator

Output parameters	SMART	ONCESG	OTSG-TH
Primary outlet temperature (°C)	268.5	268.3	264.7
Secondary outlet temperature (°C)	300	300.9	299.3
Heat transfer area (m^2, inside)	168.8	172.4	148.4(inside)
Axial height(m)	2.8	2.67~2.86	2.86
Average tube length(m)	15.8	15.1~16.1	16.2
Shell-side pressure drop (MPa)	2.57E-3	3.5 E-3	2.23E-3
Tube-side pressure drop (MPa)	0.3	0.34	0.286

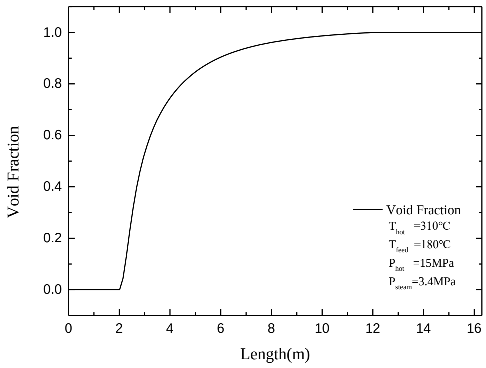

Fig.8 Void fraction distribution of SMART SG.

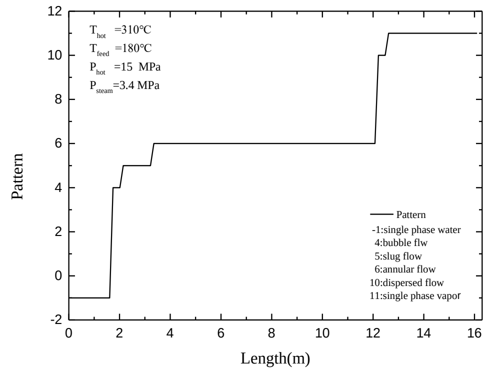

Fig.9 Pattern distribution of SMART SG.

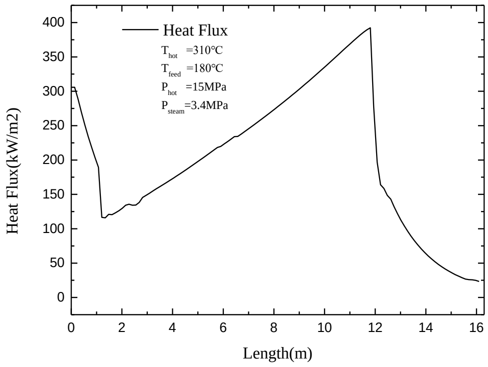

Fig.10 Heat flux distribution of SMART SG.

In the single-phase water region, the heat transfer energy from the primary side is absorbed to the secondary side fluid, causes temperature rises continuously. The heat flux drops in single phase and subcooled boiling due to the reducing of the fluid temperature difference. After entering the nucleate boiling region, bubbles begin to form on the wall, at this time the void fraction rises sharply. When the secondary side mainstream temperature reaches the saturation boiling region, flow pattern is changed to annular flow. In this region, the heat transfer intensity is increased for the boiling effect, which makes, the heat flux increasing rapidly. Due to the pressure loss during the flow, the secondary temperature may even decrease slightly. When the liquid film gradually thins out to the dry out point, vapor is in contact with the heated wall to directly obtain energy. At high gas content, the heated wall is completely covered with steam, the heat transfer deteriorates. Therefore, the heat flux will decrease continuously after transition boiling. When the steam becomes superheated, heat flux is at a minimum value.

3.2 Transient analysis

SMART is an advanced small modular reactor, for its once through steam generator utilizing helical coil type. Some transient states, such as parameters step change, may happen while the steam generators are operating. The dynamic behavior of the system was using a 10% step change in the inlet boundary parameter, which changed rapidly after the occurrence of a time step.

When a step change in the feedwater flow was applied, the parameter is shown in Fig.11. Before 150**s**, the system starts up and keeps steady state soon. After 150**s**, the feedwater flow rate is reduced from the full steady-power state 12.7 **kg/s** down 10% to 11.43 **kg/s** and kept constant within 200s, then the flow rate returns abruptly to full power condition. When the feedwater flow decreases, the length of the superheated steam regime of HOTSG is increased.

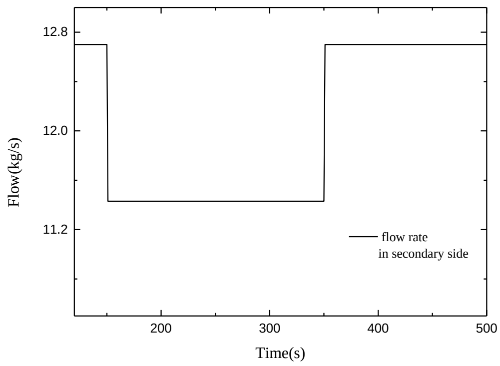

Fig.11 Flow rate step changes in secondary side.

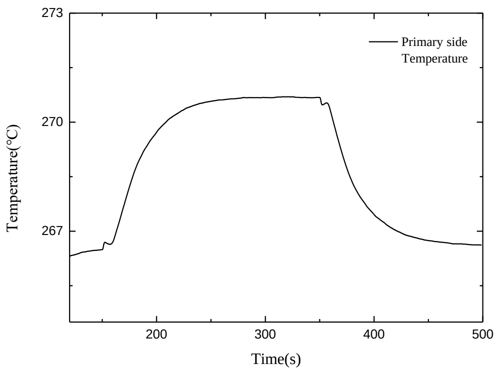

Fig.12 Primary side outlet temperature distribution.

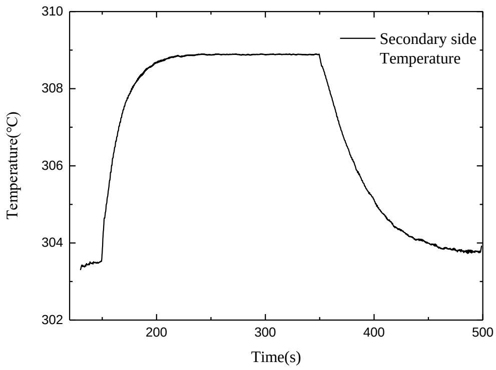

Fig.13 Secondary side outlet temperature distribution.

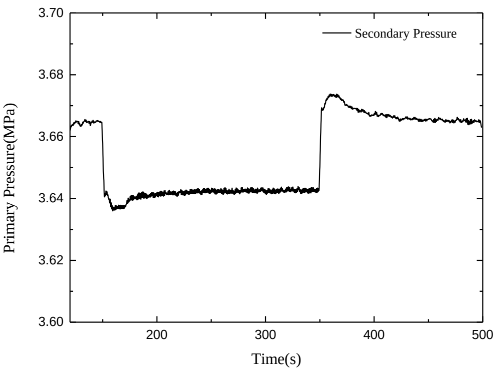

Fig.14 Secondary side outlet pressure distribution.

When the feedwater decreases, the heat of the secondary side taken away from the primary side is reduced, therefore, the primary side outlet temperature rose. In addition, the secondary side outlet temperature increases rapidly to 308.9 **℃**, which is close to primary side coolant temperature 310 **℃**. Furthermore, the primary outlet temperature lags in responses to the secondary side changes, because the primary system flow rate is high and the secondary system coolant absorbed heat is limited. Although, the instantaneous feedwater pressure and density are basically unchanged, due to the feed water flow rate is rapidly reduced, and the secondary side pressure drop is decreased as well. After 350s, feedwater flow rate temperatures of the primary and secondary sides, and pressure drop returned to the full power operating values.

4 Conclusion

A computer code OTSG-TH have been developed for thermal hydraulic analysis of a helical-coil-type once through steam generators. Firstly, calculations were carefully validated and verified with steady-state results of ONCESG code and MRX experiment. Secondly, the code was used for thermal hydraulic analyses and geometric design of a HOTSG. Overall characteristics, such as void fraction, fluid and wall temperature, pressure drop and heat flux are discussed. A postulated scenario, flow rate step changes in secondary side, was also analyzed in current study. It has showed that the OTSG-TH code can be successfully used for steady and transient state analyses of a HOTSG.

Acknowledgments

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[Nomenclature]

Greek symbols

α	Void fraction(-)
ρ	Density(kg/m^3)
λ	Thermal conductivity(W/m·K)
μ	Dynamic viscosity(Pa·s)
Γ	Mass transfer(kg)
Δ	Roughness(-)

Nomenclature

d	Inner tube diameter(m)
d_0	Outer tube diameter(m)
D	Helix diameter(m)
f	Friction coefficient(-)
Nu	Nusselt number
P	Pressure(Pa)
Pr	Prandtl number
Re	Reynolds number

Subscripts

l	Liquid phase
g	Gas phase

lg	Phase transfer
gl	Phase transfer

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