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Thermal Hydraulic Modeling of Once-Through Steam Generator by Two-Fluid U-Tube Steam Generator Code

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ABSTRACT

The THERMIT U-tube steam generator (THERMIT-UTSG) code was used for evaluation for the parametric study of a scaled once-through pressurized water reactor steam generator (OTSG) made by Babcock & Wilcox. The results of the code were compared to the experimental data of the 19-tube OTSG and a simple heat transfer code that was developed by Osakabe. The main calculated thermodynamic parameters were primary-secondary fluid temperatures, tube wall internal and external temperatures that were subjected to primary and the secondary fluid, and the secondary fluid vapor quality. The assessed code can be used for modeling the OTSGs with some modification. The results of THERMIT-UTSG were in agreement with the experimental results and the prediction of Osakabe's numerical model.

INTRODUCTION

Steam generators are designed to remove the heat generated in the reactor vessel and, by utilizing the once-through concept, to produce dry, superheated steam at their exits [1]. Steam generators are categorized into two types, namely the recirculation-type steam generators that are known as the U-tube steam generator (UTSG) and the once-through type that are known as the once-through steam generator (OTSG) [2]. The latter is a vertical, straight, tube-and-shell heat exchanger that produces superheated steam at constant turbine throttle pressure throughout the power range. OTSG internal structural details are simpler than that of the UTSG. However, its heat transfer regions are more complex due to several transitions in the secondary fluid. Figure 1 shows the cross-sectional view of a Babcock & Wilcox (B&W) OTSG. The water convection regime is assumed to be in the primary side of the steam generator, while three heat transfer regions will develop in the secondary side as feedwater is converted to superheated steam. The heat transfer regions that start at the lower tube sheet are the nucleate boiling, film boiling, and superheat regions. For simple calculation, it is assumed that the entrainment has no effect on dryout.

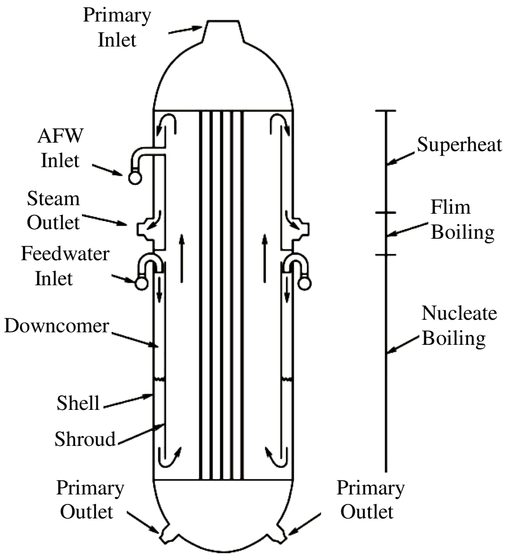

Fig. 1. Cross-sectional view of an OTSG [1].

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Moreover, steam convection heat transfer was ignored at the superheat region [3]. The reactor coolant enters the upper plenum through a single inlet nozzle, flows downward through Inconel tubes, and passes through two outlet nozzles in the lower plenum. Feedwater enters the annulus area via the feedwater nozzle connections just above the middle of the shell and is sprayed downward. The cold feedwater draws steam from the tube bundle region through the aspirating port, a gap between the upper and lower shrouds. The steam is condensed as it preheats the feedwater. The feedwater is at saturation temperature when it reaches the lower tube sheet. The saturated feedwater is boiled to produce steam in the lower portion of the tube bundle, and then superheated along the remaining tube bundle length. The superheated steam is directed downward through the steam annulus and leaves the OTSG through two steam nozzles that are located just above the feedwater nozzle connections. OTSG can be modeled in different ways. When OTSG is modeled by using existing system codes, such as RELAP5, which use fixed boundaries, sometimes they allow errors within one control volume range on the secondary side boundaries [4-5]. However, researchers extensively analyzed U-tube steam generators by using RELAP5 [6].

Tzanos developed a movable boundary model for OTSG analysis, which is dependent on specific empirical correlations and assumed a constant pressure within heat transfer regions [7]. Berry solved only one energy and continuity equations for the OTSG and included the pressure drop calculation for the OTSG in the overall system via an external pipe model [8]. Yoon *et al.* developed a movable boundary formulation which used a variable number of control volumes for each heat transfer region [9]. The resulting ONCESG code was designed to model the helically-coiled tubes of the OTSG of the 300-MWt integral reactor of the Korea Atomic Energy Research Institute. They benchmarked their code physical models by design data. That code showed general agreements with the published data [9].

In this study, THERMIT-UTSG code was used to model the two-phase condition in a small-sized OTSG. The results are comparable with Osakabe's model and experimental data.

EXPERIMENTAL METHODS

The 19-tube steam generator experimental data was used to evaluate the simulation capability of THERMIT-UTSG for modeling the OTSG. Figure 2 shows the 19-tube B&W test section.

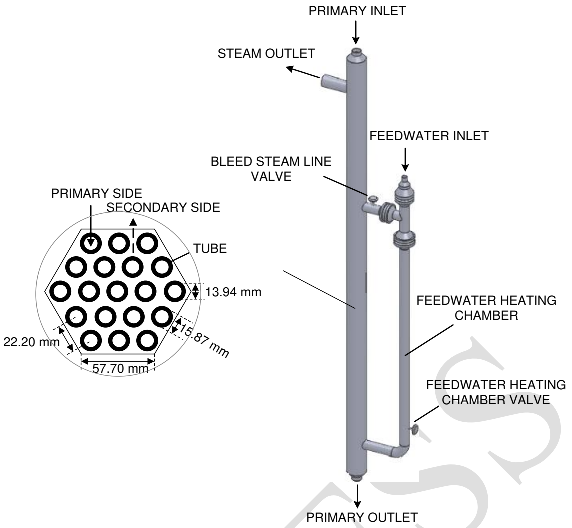

Fig. 2. Cros-sectional view of B&W OTSG test section with 19 tubes [10].

The primary fluid enters the tubes at the top and flows downward through the tubes. The secondary fluid enters at the bottom and flows upward in the shell side, as a counter current heat-exchanger. Table 1 shows the steady-state experimental condition.

Table 1. Initial conditions of Babcock & Wilcox 19-tube steam generator experiment scaled for a 3240 MW reactor [3]

Parameter	Values
Primary inlet temperature (°K)	572.0
Primary flow rate (kg/s)	16800.
Primary inlet velocity (m/s)	5.6
Primary pressure (MPa)	15.3
Primary flow area (m^2)	20.0
Secondary inlet temperature (°K)	525.0
Secondary inlet velocity (m/s)	0.3
Secondary pressure (MPa)	7.4
Secondary flow rate (kg/s)	1764.
Secondary heat transfer area (m^2)	3.48×10^4
Tube length (m)	16.0

Osakabe heat transfer model

The simple heat transfer code that was developed by Osakabe is mainly based on Chen's correlations in the subcooled boiling and saturated boiling regions. In the code, Chen's correlations for the forced convective boiling were adopted for the accurate calculation and the effects of the entrainment on the dryout process was ignored. For more details, see Reference [3].

THERMIT-UTSG

In this study, THERMIT-UTSG, an advanced multidimensional developed version of THERMIT-

2 U-tube steam generator analysis code, was used to model the OTSG under study. This code has two pairs of mass, energy, and momentum conservation equations for each of the three-dimensional formulation [11-14].

Conservation of vapor mass

$$\frac{\partial}{\partial t}(\alpha\rho_v)+\nabla.\left(\alpha\rho_v\vec{V}_v\right)=\Gamma-W_{tv} \quad (1)$$

Conservation of liquid mass

$$\frac{\partial}{\partial t}[(1-\alpha)\rho_l]+\nabla.[(1-\alpha)\rho_l\vec{V}_l]=-\Gamma-W_{tl} \quad (2)$$

Conservation of vapor energy

$$\frac{\partial}{\partial t}\left(\alpha\rho_v e_v\right)+\nabla.\left(\alpha\rho_v e_v\vec{V}_v\right)+P\nabla.\left(\alpha\vec{V}_v\right)+P\frac{\partial\alpha}{\partial t}=Q_{wv}+Q_i-Q_{tv} \quad (3)$$

Conservation of liquid energy

$$\frac{\partial}{\partial t}[(1-\alpha)\rho_l e_l]+\nabla.[(1-\alpha)\rho_l e_l\vec{V}_l+P\nabla.[(1-\alpha)\vec{V}_l-P\frac{\partial\alpha}{\partial t}=Q_{wl}-Q_i-Q_{tl} \quad (4)$$

Conservation of vapor momentum

$$\alpha\rho_v\frac{\partial\vec{V}_v}{\partial t}+\alpha\rho_v\vec{V}_v.\nabla\vec{V}_v+\alpha\nabla P=-\vec{F}_{wv}-\vec{F}_{iv}+\alpha\rho_v\vec{g}-\vec{F}_{tv} \quad (5)$$

Conservation of liquid momentum

$$(1-\alpha)\rho_l\frac{\partial\vec{V}_l}{\partial t}+(1-\alpha)\rho_l\vec{V}_l.\nabla\vec{V}_l+(1-\alpha)\nabla P=-\vec{F}_{wl}-\vec{F}_{il}+(1-\alpha)\rho_l\vec{g}-\vec{F}_{tl} \quad (6)$$

In addition, constitutive equations were formulated for each fluid. Since this model can handle non-equilibrium two-phase flows, the THERMIT-UTSG code has the capability for analysis of complicated transients. Since the code enjoys a judicious compromise method between implicit and explicit treatments known as implicit continuous fluid Eulerian method, flow conditions can be determined with minimum restrictions [11-14].

Figure 3 shows the 19-tube OTSG with its channels optimized to be simulated with THERMIT-UTSG code.

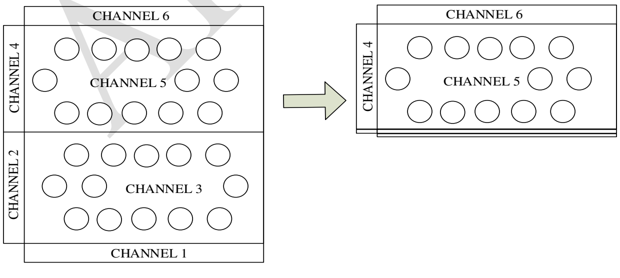

Fig. 3. Typical reduced channel layout for simulation with THERMIT-UTSG.

According to geometry definitions in the code, the cells that contained channels 1 to 3 were considered as small. Channel 5 was the real-size OTSG downward flow tubes. Channel 3 was the upward flow evaporator. Channel 4 and channel 6 were the paths for downcomer. In order to analyze OTSG by THERMIT-UTSG, we have neglected separators, transverse momentum, and pressure drop due to geometry.

RESULTS AND DISCUSSION

Figure 4 shows the experimental and calculated temperature distributions in the 19-tube OTSG experiment.

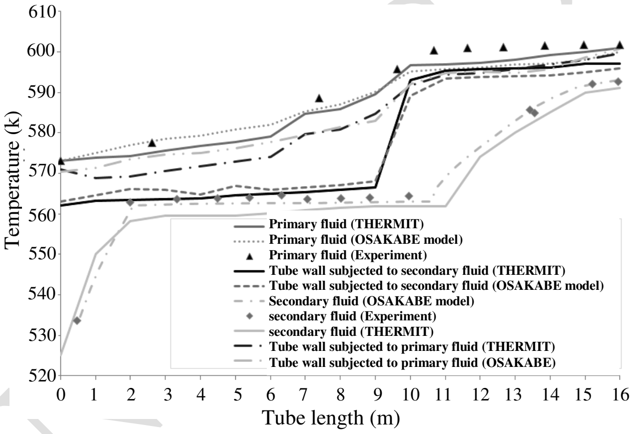

Fig. 4. Calculated and experimental temperature distributions along the tube and its wall.

The calculated temperatures were primary fluid temperature, secondary fluid temperature, tube wall temperature subjected to primary fluid, and tube wall temperature subjected to secondary fluid. The temperature of the downward primary fluid decreased in the tubes. The secondary fluid entered at the bottom of the test section and then heated up to saturation temperature. After the dryout region of secondary fluid, the temperature of the tube wall increased and the fluid began to superheat. It is obvious from the figure that the temperatures of the primary and the secondary fluid were well computed by the THERMIT-UTSG code. Note that because of the large temperature gradients between the primary side and the secondary side (as shown in Fig. 4), the heat conductivity of the tube wall had an important role in the OTSG heat transfer. Figure 5 shows the calculated mass quality of the vapor.

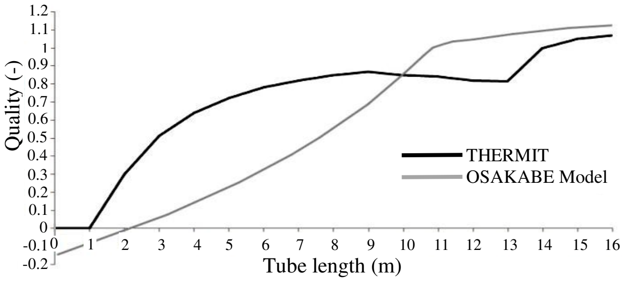

Fig. 5. Calculated quality along tube in 19-tube steam generator experiment.

The mass quality of the secondary side was greater than 1.0 that means the increasing rate of the transferred heat becomes very small. Therefore, it is obvious that over a vapor single phase region the ramp rate or the slope of the curve is smooth. The transferred heat from the primary side to the secondary side gradually increased to the dryout point. At the dryout point, the secondary vapor quality exceeded 1.0 and the increasing rate of the integrated heat transferred became very small. It is obvious from the figure that THERMIT resulted in error in determining the dryout point with respect to Osakabe's model.

CONCLUSION

A scaled once-through steam generator was modeled using THERMIT-UTSG code. The THERMIT code was evaluated in comparison with Osakabe's model and the Babcock & Wilcox OTSG experiments. The calculated temperatures by the code were in good agreement with experimental data and Osakabe's model. However, the results of vapor quality exhibited an error. The THERMIT-UTSG code is an adaptable tool for modeling a once-through steam generator. In addition, since THERMIT-UTSG code uses complete two-phase model equations, it can predict thermal hydraulic parameters very well.

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Nomenclature		
	$\boldsymbol{\alpha}$	Void fraction
	$\boldsymbol{\rho}$	Density (kgm^{-3})
	$\boldsymbol{\Gamma}$	Volumetric vapor generation rate $(kgm^{-3}s^{-1})$
	P	Pressure (Nm^{-2})
	F	Momentum $(kgm^{-2}s^{-2})$
	e	Internal energy (kj/kg)
	W	Mass exchange due to turbulent fluctuations
	$\boldsymbol{Q}$	Energy source term (Wm^{-3})
	g	Gravitational acceleration (ms^{-2})
	$\vec{\boldsymbol{V}}$	Velocity vector (m/s)
	t	Time coordinate (s)
Subscript		
	$\boldsymbol{i}$	Interfacial exchange term
	$\boldsymbol{tv}$	Turbulent vapor
	$\boldsymbol{tl}$	Turbulent liquid
	$\boldsymbol{l}$	Liquid phase
	$\boldsymbol{v}$	Vapor phase
	$\boldsymbol{w}$	Wall