General Heat Exchanger Modeling for Quasi-Steady Small Modular Reactor Heat Source Simulation

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ABSTRACT: In this research, a detailed steam generator model is developed to be utilized in the nuclear combined heat and power cycle / cogeneration system model. Also, general off-design heat exchanger component model is developed with modified effective-NTU method to calculate the exchanged amount of heat energy during off-design conditions that can be used for any heat exchangers with phase-change component, whether it be a reheater, a feedwater heater, or even a steam generator. The purpose of this research is to develop a general heat exchanger model for a system code used to simulate a typical small modular reactor off-design quasi-steady state, which will ultimately be used for simulating the quasi-steady small-modular reactor heat source for a typical nuclear cogeneration system. The scope of current research is focused on analyzing the off-design quasi-steady state and thus does not include how the transient system behaves between the end states.

1. Introduction

- **Currently many codes are being developed to simulate nuclear cogeneration but with either simple assumption on transferred heat or using time-extensive models**
- **When the analyzed system is off from its maximum guaranteed rating (MGR) condition, the power transferred from primary to secondary system of nuclear plant may not be equal to its 100% steady state condition and thus should be analyzed separately**
- **One of the most complex models for the nuclear system is the steam generator (SG), introducing one of the challenges in developing a fast system code**
- **A challenge exists in developing a light enough SG model and heat exchanger model that can still simulate for the fast system model with reasonable accuracy**

2. Methods

- **For the general quasi-steady heat exchanger models, effectiveness Number of Transfer Units (ε-NTU) method was used to calculate the rate of heat transfer in the counter-current heat exchangers in the quasi steady state analysis**
- **What is modified from traditional ε-NTU method is the inclusion of pseudo-two-phase specific heat by deriving representative specific heat to account for both sensible (S) and latent (L) heat of the fluid for hot (H) and cold (C) coolants**

$$C_{p,i} = C_{p,i,S} + C_{p,i,L}, \qquad i = H \text{ or } C$$

$$C_{p,H,S} = \frac{C_{p,H,in} \times (T_{H,in} - T_{H,sat}) + C_{p,H,out} \times (T_{H,sat} - T_{H,out})}{T_{H,in} - T_{H,out}}$$

$$C_{p,C,S} = \frac{C_{p,C,in} \times (T_{C,sat} - T_{C,in}) + C_{p,C,out} \times (T_{C,out} - T_{C,sat})}{T_{C,out} - T_{C,in}}$$

$$C_{p,H,L} = \frac{\min(h_{H,in}, h_{H,g}) - \max(h_{H,out}, h_{H,f})}{T_{H,in} - T_{H,out}}$$

$$C_{p,C,L} = \frac{\min(h_{C,out}, h_{C,g}) - \max(h_{C,in}, h_{C,f})}{T_{C,out} - T_{C,in}}$$

- **For an off-design operation SG analysis, general heat exchanger model is first used to calculate the overall heat rate transferred from primary side to secondary side of the steam generator (i.e. final SG model is a combination of the general heat exchanger model plus the detailed SG model)**
- **For the detailed SG model, a characteristic SG tube is divided into number of equally-sized *N*-nodes**
- **Starting from initial guess of linearly distributed enthalpy for the primary and secondary side, pressure, and tube conductivity, outer and inner tube surface temperatures are found for each *jth* node from solving a matrix equation "AT=B" derived from heat balance.**

$$\mathbf{A} = \begin{bmatrix} h_{p,j}A_{outer,j} & h_{p,j}A_{inner,j} \\ \frac{k_j A_{central,j}}{\Delta r} & -h_{s,j}A_{inner,j} - \frac{k_j A_{central,j}}{\Delta r} \end{bmatrix} \quad \mathbf{B} = \begin{bmatrix} h_{p,j}A_{outer,j}T_{p,j} + h_{s,j}A_{inner,j}T_{s,j} \\ -h_{s,j}A_{inner,j}T_{s,j} \end{bmatrix} \quad \mathbf{T} = \begin{bmatrix} T_{outer,j} \\ T_{inner,j} \end{bmatrix}$$

- **At each node, gravitational, frictional, accelerational, and form pressure drop are calculated and summed to calculate total pressure drops for primary and secondary sides in the SG**
- **Use calculated tube surfaces to update the enthalpy values in each node by calculating heat transferred in each node using the primary and secondary coolant information as well as outer and inner tube surface temperatures**
- **Repeat above steps with updated enthalpies, pressures, and temperatures until convergence for the detailed SG model**

3. Results

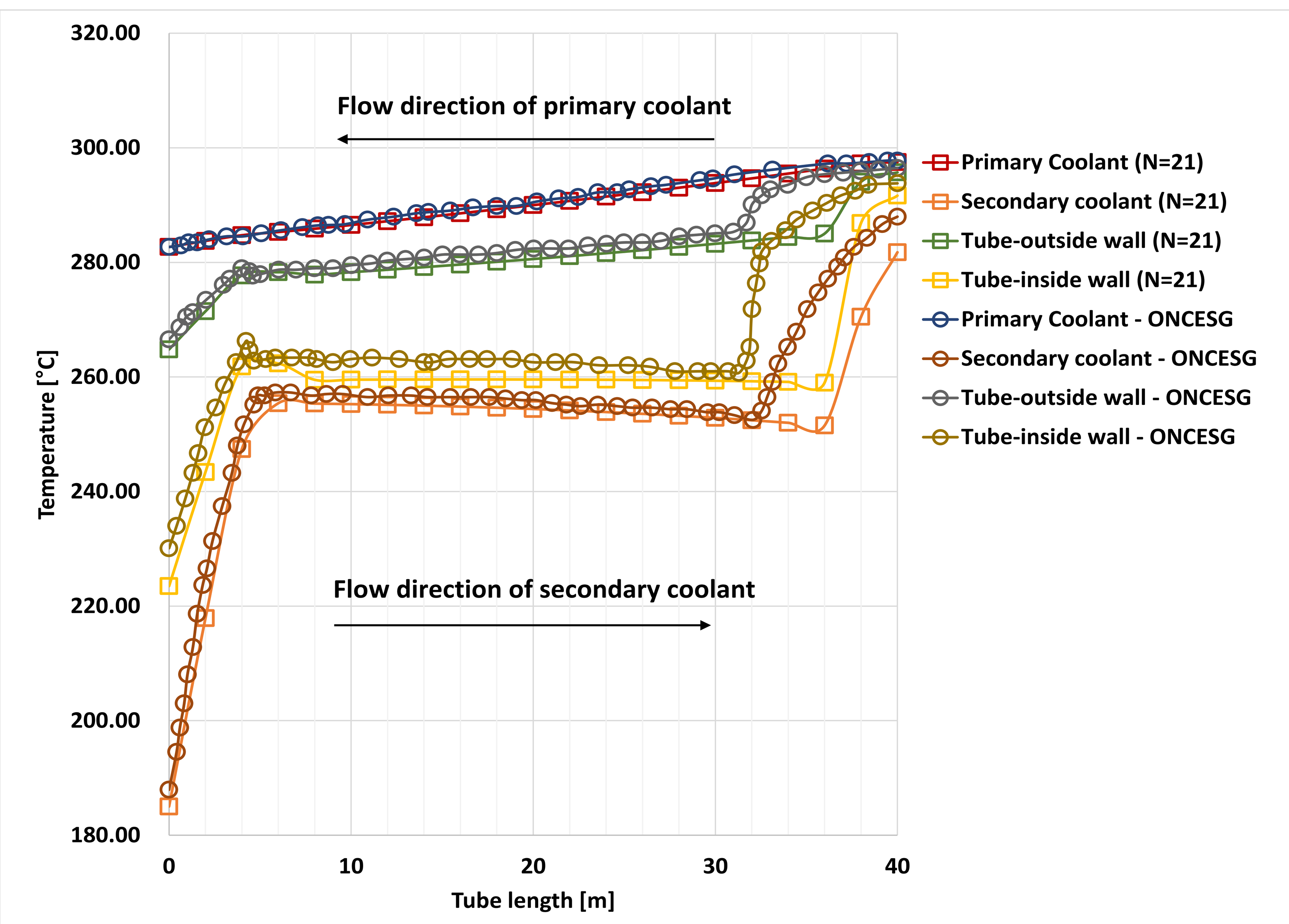

Figure 1. MRX SG Temperature Profile Comparison for the detailed SG and ONCESG [1]

Table 1. Comparison with MRX SG and old SMART SG Results [1]

	MRX	ONCESG Case 1	ONCESG Case 2	Detailed SG Model
P_{hot} [MPa]	12	12	12	12
T_{hot} [°C]	297.5	297.5	297.5	297.5
P_{steam} [MPa]	4	4	4	4.03
T_{feed} [°C]	185	185	185	185
T_{cold} [°C]	282.5	282.5	282.5	282.7
T_{steam} [°C]	289	289	289	282
Shell-side pressure drop [MPa]	9.0E-3	1.2E-2	1.2E-2	2.23E-2
Tube-side pressure drop [MPa]	0.64	0.42	0.49	0.37
	SMART (old)	**ONCESG Case 1**	**ONCESG Case 2**	**Detailed SG Model**
P_{hot} [MPa]	15	15	15	15
T_{hot} [°C]	310	310	310	310
P_{steam} [MPa]	3.4	3.4	3.4	3.42
T_{feed} [°C]	180	180	180	180
T_{cold} [°C]	268.5	268.3	268.3	268.7
T_{steam} [°C]	300	300.9	300.9	294.4
Shell-side pressure drop [MPa]	2.57E-2	3.5E-2	3.5e-2	2.2E-2
Tube-side pressure drop [MPa]	0.3	0.34	0.35	0.28

Table 2. The Off-Design Heat Exchanger Model Validation Results for the SMART100 for MGR and VWO Operation Conditions [2]

Steam Generator (SG), Feedwater Heaters (FWH), and Reheaters (RH)	Simulated Hot and Cold Line Outlet Results (MGR)			Heat Balance Diagram	Ratio of Simulated Rate of Heat Transfer to the HBD Values
	Hot: Drain Outlet Enthalpy (kJ/kg)	Cold: Feedwater / Main Steam Outlet Enthalpy (kJ/kg)	Rate of Transferred Heat (MW)	Rate of Transferred Heat (MW)	
SG	1306.2	2891.2	361.17	364.24	0.992
RH1	1055.7	2876.0	17.22	17.65	0.976
RH2	1148.1	2934.5	6.87	6.89	0.997
LPFWH1	207.55	259.89	10.62	10.35	1.027
LPFWH2	286.06	338.21	11.05	10.75	1.028
LPFWH3	369.32	413.92	10.72	10.39	1.032
LPFWH4	450.09	479.16	9.312	8.924	1.044
HPFWH1	678.20	763.73	24.12	25.93	0.930
HPFWH2	783.44	993.36	45.70	45.88	0.996
Steam Generator (SG), Feedwater Heaters (FWH), and Reheaters (RH)	**Simulated Hot and Cold Line Outlet Results (VWO)**			**Heat Balance Diagram**	**Ratio of Simulated Rate of Heat Transfer to the HBD Values**
	Drain Outlet Enthalpy (kJ/kg)	**Feedwater / Main Steam Outlet Enthalpy (kJ/kg)**	**Rate of Transferred Heat (MW)**	**Rate of Transferred Heat (MW)**	
SG	1299.6	2901.8	376.73	380.03	0.991
RH1	1160.0	2871.9	17.379	18.795	0.925
RH2	1050.9	2936.1	6.8513	6.514	1.052
LPFWH1	238.62	257.29	10.76	11.40	0.944
LPFWH2	308.74	339.57	11.20	11.35	0.987
LPFWH3	392.90	416.35	10.90	10.94	0.997
LPFWH4	476.40	482.47	9.48	9.41	1.007
HPFWH1	659.42	756.11	26.28	27.62	0.952
HPFWH2	908.82	991.61	45.90	48.86	0.939

4. Conclusion

- **Models to calculate the transferred heat for quasi-steady analysis of the small modular reactors were developed**
- **Detailed SG model was validated with the results from the ONCESG code for MRX SG and old SMART SG design from 2000 [1]**
- **General heat exchanger model with modified effective-NTU method was validated with the heat balance diagram of the SMART100 Safety Analysis Report [2]**
- **These models may be used in simulating the off-design steady analysis of the small modular reactor for nuclear cogeneration / combined heat and power cycle simulations when it is not given that the transferred heat in each heat exchanger may stay constant from the normal MGR steady state conditions.**

References used for Validation of the Models

[1] Yoon, Juhyeon, et al. "Development of a computer code, ONCESG, for the thermal-hydraulic design of a once-through steam generator." Journal of nuclear science and technology 37.5 (2000): 445-454.

[2] KHNP, KAERI, KACARE, SMART100 Standard Safety Analysis Report, 2019