Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 18-19, 2017

Design and Simulation for a Helical-coil Steam Generator of FINCLS Facility

Eunkoo Yun [a], Hwang Bae [a], Sung Uk Ryu[a], Byong-Guk Jeon[a], Jin-Hwa Yang[a], Sung-Jae Yi [a], Hyun-Sik Park [a*]
[a]*Korea Atomic Energy Research Institute, 989-111 Daedeokdaero, Yuseong, Daejeon, 305-353, Korea*
[*]*Corresponding author: hspark@kaeri.re.kr*

1. Introduction

The FINCLS is a simplified test loop derived from the SMART-ITL (Integral Test Loop for SMART) [1] for investigating the physical behaviors on both of single- and two-phase natural circulations. In SMART design, the helical-coil steam generator (SG) with once-through flow path is employed in vertical arrangement on the secondary stream. This geometrical feature ensures effective heat transfer area for producing superheated vapor. The tube outlet is near the shell inlet, so that high-temperature heat in the primary fluid can be effectively transferred to the secondary fluid. Therefore, the superheated vapor can be obtained directly through the steam generator. However, due to the absence of a superheating device, the downstream of SG secondary side must be ensured to be completely converted into the vapor phase with a sufficient degree of superheating, to prevent the introduction of liquid droplets into the turbine. Because of these features, the performance validation test for SG over a wide operating range is strongly recommended to ensure system robustness and safety.

This study focuses on the design and simulation for SG, which applies to the FINCLS facility. The design requirement of the SG is to be capable of the scaled full performance in heat transfer, so that the helically coiled single-tube arrangement is adopted for the secondary stream. To determine the major geometrical parameter of the SG, a generalized moving-boundary algorithm [2] was employed with appropriate correlations of flow heat transfer coefficient. Then, a simulation model was established for predicting the performance of SG over a wide operating condition, as well as for identifying the availability of present SG design.

2. Description of FINCLS Facility

Fig. 1 shows the schematic diagram of the FINCLS including the primary and secondary loops. The main components and pipe system are established by using the pipe arrangements within commercially available schedules.

The main purpose of the FINCLS is to implement the parametric study for the natural circulation phenomena in the SMART design. In the FINCLS design, the flow area and fluid inventory volume were scaled down to 1/64 from the reference system, SMART-ITL, while the height of test facility was conserved to that of reference system for avoiding the distortion in the thermal-hydraulic characteristics.

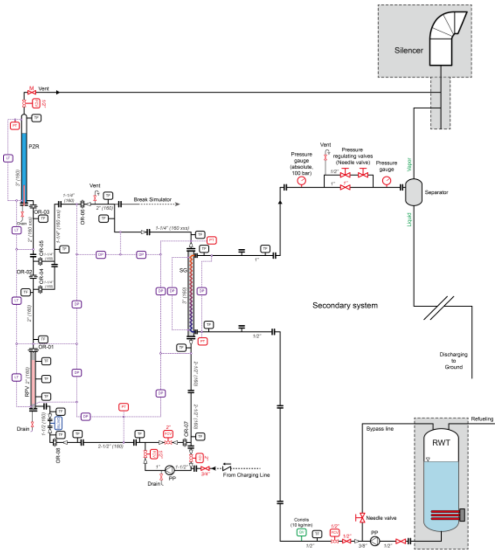


Fig. 1. Schematic diagram of FINCLS including the primary and secondary systems.

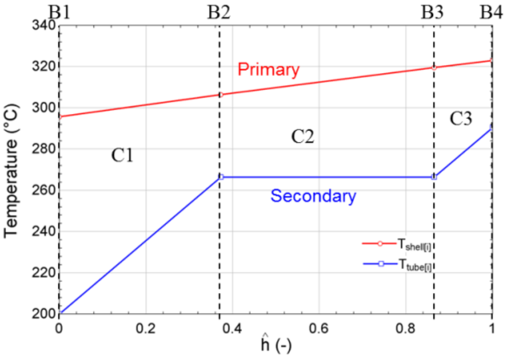


Fig. 2. Targeted temperature profile between the primary and secondary streams through the SG.

3. Design of SG

The design of SG is focused on satisfying the scaled full capability in heat transfer, as well as to be capable of sufficient controllability for the heat removal during various experimental tests. The temperature profiles corresponding to the target performance are indicated in Fig. 2, as a function of the normalized specific enthalpy.

Several geometrical parameters are pre-determined by the volume scaling ratio, as well as by the limitation in usage of commercial pipe schedules. The pre-determined shell inner diameter and the coil diameter are 66.64 mm and 40.0 mm, respectively. The helically-coiled tube is manufactured by using 3/8 inch commercial stainless steel tube with thickness of 1.2

mm. The total height for the active heat transfer region is 4.4 m. Under those fixed geometrical conditions, the pitch of helical coil could be considered as the major design parameter for the SG design, and should be appropriately determined for achieving the targeted capability in heat transfer.

A generalized moving-boundary algorithm was employed for the SG design. As shown in Fig. 3, in this case totally three cells (C1 to C3) can be considered with the four boundaries (B1 to B4). The secondary side in SG consists of both ends of SG and two saturation points. The actual heat transfer rate for each cell is known from the secondary stream.

$$\dot{Q}_j = \dot{m}_s(h_{s,j+1} - h_{s,j}) \qquad (1)$$

Then, the required overall thermal conductance (UA) for each cell can be obtained by

$$UA_{req,j} = \frac{\dot{Q}_j}{LMTD_j} \qquad (2)$$

The mean overall heat transfer coefficient for each cell (tube outer) can be given by

$$U_{o,req,j} = \frac{1}{\frac{1}{\alpha_{p,j}} + \frac{\ln(r_o/r_i)}{2\pi kL}A_{p,j} + \frac{A_{p,j}}{\alpha_{s,j}A_{s,j}}} \qquad (3)$$

To obtain the heat transfer coefficient of primary side, a non-dimensional relation reported by Ramachandra et al. [3] was used. For the heat transfer coefficient of secondary side, Gnielinski [4] and Chen [5] correlations were utilized for the heat transfer coefficients for single- and two-phase, respectively. Santini et al. [6] reports that Chen correlation shows an acceptable error within 15-20 % with experimental results, despite to the absence of curvature effect in the correlation. The required heat transfer area (tube outer) for each cell can be obtained by

$$A_{o,req,j} = \frac{UA_{req,j}}{U_{o,req,j}} \qquad (4)$$

It should be noted that the total required heat transfer area ($\sum A_{o,req,j} = A_{o,req}$) must be more than the total available heat transfer area ($A_{o,avail} = \pi d_{tube,o} L_{tube}$) for satisfying the targeted capability in heat transfer.

Fig. 3 shows the resulting required and available heat transfer areas depending on the coil pitch. As the coil pitch increases, the required heat transfer area increases due to the decrease in the heat transfer coefficient of the primary side. The trade-off relation can be found between required and available heat transfer areas. Consequently, the pitch is determined as 16 mm which corresponds to about 5 % margin design in heat transfer area.

Fig. 4 shows the detailed design related to other concerns in the structural robustness. The coil pitch of helical tube is shown in Fig. 4 (a). Since the height of helical coil is 4.4 m which is extremely longer than the coil diameter, the vertical guide structure is essential to prevent the bending of coil body. The four guides to support the helical coil body are employed by attaching the inner surface of annulus, as shown in Fig. 4 (b). The dimensions of guide structure are indicated in Fig. 4 (c) with the cross sectional view.

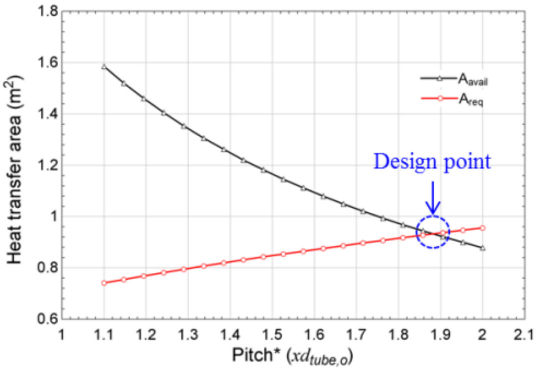
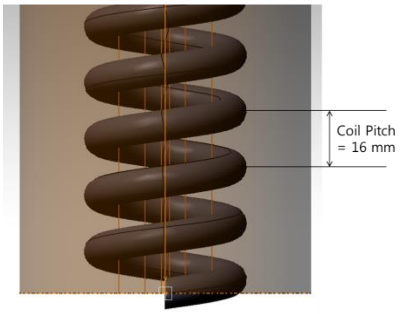
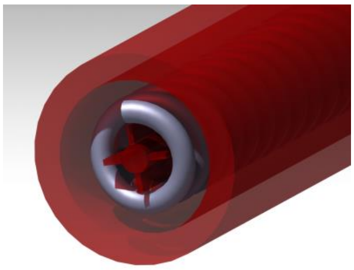


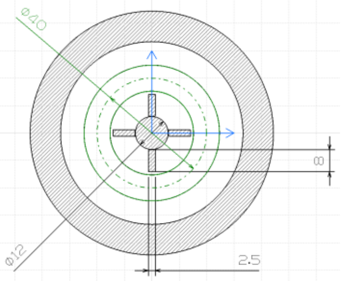
Fig. 3. Required and available heat transfer areas of the SG depending on the coil pitch



(a) Coil pitch



(b) Guide structure for helical coil



(c) Guide structure for helical coil

Fig. 4. Detail design of the SG

4. Simulation Model and the Preliminary Test

Fig. 5 shows the calculation process of SG simulation model being based on the moving-boundary algorithm. This model can be used to predict the result of heat transfer process through SG for any phase changes on the secondary stream.

As a preliminary test of the simulation model, a specific case for 50 % core power operations is conducted for variable mass flow rates of secondary side, under the fixed input condition of primary side. As presented in Fig. 6, the result shows the physically reasonable predictions. The excessive mass flow rate of secondary fluid imposes the quality at the secondary downstream to be decreased, as shown in Fig. 6 (a). Once the quality decreases, the rate of increase in heat transfer rate is remarkably reduced. Those results also can be identified by the temperature variations of both streams, as shown in Fig. 6 (b). In the future, the model will be validated by the experimental tests with FINCLS facility.

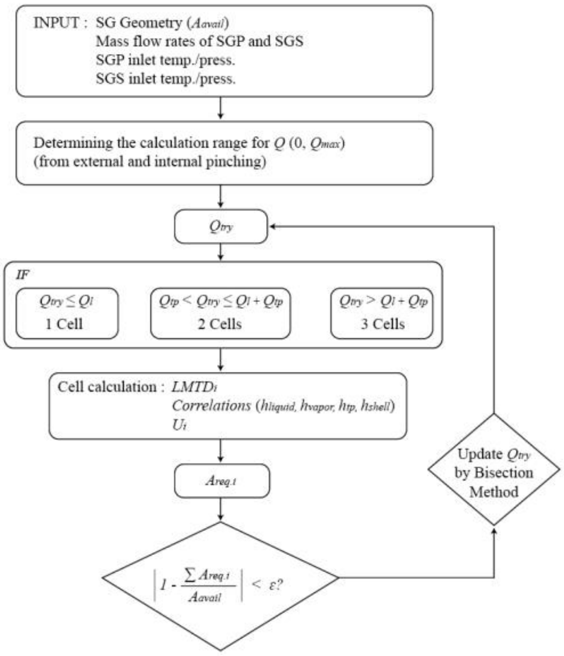
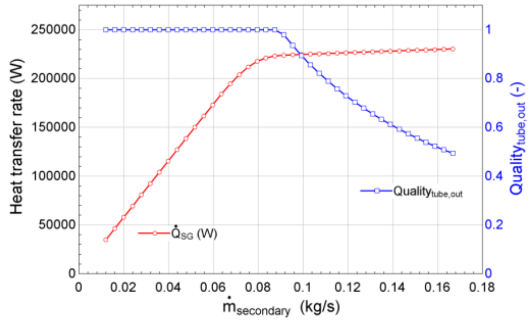
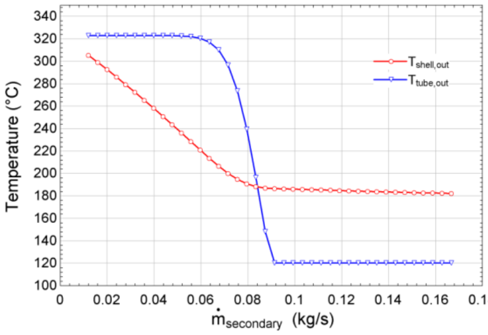


Fig. 5. Algorithm used in the SG simulation model



(a) Heat transfer rate and the quality of secondary fluid at the SG outlet



(b) Outlet temperatures for primary and secondary streams

Fig. 6. Simulation results for 50 % core power operation

5. Conclusions

This study reports on the design and simulation of SG for the FINCLS facility. For achieving a successive design, a generalized moving-boundary algorithm was applied with appropriate heat transfer correlations. For satisfying the target capability in heat transfer, the coil pitch is consequently determined as 16 mm, which corresponds 5 % of the marginal rate of heat transfer area.

The simulation model to predict the heat transfer process through the SG was proposed, and established by utilizing the generalized moving-boundary algorithm. The results of preliminary test show the physically reasonable predictions for any phase changes in the secondary stream. The models used in design and simulation will be carefully validated by various experimental tests on the FINCLS facility.

ACKNOWLEDGEMENT

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIP). (No. 2016M2C6A1004894)

REFERENCES

[1] K. K. Kim et al., SMART: The First Licensed Advanced Integral Reactor, Journal of Energy and Power Engineering, 8, pp.94-102, 2014.

[2] I. H. Bell et al., A generalized moving-boundary algorithm to predict the heat transfer rate of counterflow heat exchangers for any phase configuration, Applied Thermal Engineering, Vol.79, pp.192-201, 2015.

[3] P. Ramachandra et al., Designing a helical-coil heat exchanger, Chemical Engineering, Vol.92-24, pp.85-88, 1982.

[4] V. Gnielinski, Helically coiled tubes of circular cross section, in: G.F. Hewitt (Ed.), HEDH-Heat Exchanger Design Handbook, vol. 2, Begell House, New York, 2008.

[5] J.C. Chen, Correlation for boiling heat transfer to saturated fluids in convective flow, Ind. Eng. Chem. Process, pp. 322–329, 1966.

[6] Santini, Lorenzo, et al., Flow boiling heat transfer in a helically coiled steam generator for nuclear power applications, International Journal of Heat and Mass Transfer, 92, pp.91-99, 2016.