A SIMPLE AND EFFICIENT STEAM GENERATOR DESIGN FOR INTEGRAL SMRs

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Thermal-hydraulic performance of a steam generator (SG) depends on its composition, geometry and orientation as well as on properties of the working fluid. Over the time, several SG designs have been evolved with efficient heat transfer characteristics. Helical-coiled tube SG is one of the successful designs. Its large surface area per unit volume gives it benefit of outstanding heat transfer ability. However, requirement of the integral reactor designs to allow boiling inside tubes causes instabilities in helical-coiled steam generator. To overcome this problem, a new steam generator design for integral SMRs has been proposed in this work. Although the design is simple, however, it is robust against steam side instabilities. Thermal-hydraulic analysis of the proposed design has been carried out using RELAP5/SCDAP Mod 4.0. The results are compared with helical-coiled steam generators being used in integral SMRs. It is found from the analysis that the proposed design has heat transfer characteristics comparable to that of helical steam generator.

I. INTRODUCTION

To meet future energy challenges, advanced technologies are being implemented for long term deployment of nuclear power plants. Extensive research is being carried out worldwide to develop innovative Small Modular Reactors (SMRs) with salient features of simplified technology, inherit passive safety, sustainability and reliability, proliferation-resistance, and economic viability. The International Atomic Energy Agency (IAEA) has launched a program “International Project on Innovative Reactors (INPRO)” to enhance cooperation among the member states for development of SMRs. About fifty concepts and designs of innovative SMRs including all principle reactor types (e.g. water cooled, liquid metal cooled, gas cooled, and molten salt cooled reactors) are under development in different countries around the world, the current status of these SMRs can be found in references [1-6].

The most attractive design is the natural circulation based SMRs. The reduced power levels in small reactors permit plant simplification to a great extent and allow use of passive safety systems that would make nuclear reactors much safer. SMRs have compact design that integrates primary circuit, steam generator and control rod drive mechanism (CRDM) into a single reactor pressure vessel (RPV). The integral designs in which water is used as primary coolant with reliance on natural circulation can make safety systems less dependent upon active components like pumps and diesel generators [1].

At present, many small reactors based on natural circulation are being designed and some are in operation in different countries. These systems operate at full reactor power using natural circulation to drive fluid flow through the core. Natural circulation is established as a result of the primary coolant density difference in the core and the elevated steam generator.

The core heat removal ability of a steam generator depends on several design aspects for example its composition, geometry, orientation, and fluid properties. Over the time, several SG designs have been evolved with efficient heat transfer characteristics. Keeping in view that coiled tubes have widely been used worldwide in heating and refrigerating plants, helical coiled tube SG is an appealing design. Due to its large surface area per unit volume, it is capable of high thermal performance. However, integral reactors that incorporate helical coil steam generators allow boiling in tubes. This is a source of steam side instabilities [2].

In this paper, a new steam generator design for integral SMRs that is robust against steam side instabilities has been proposed. Primary objective of the present work is to investigate thermal-hydraulic behavior of the proposed design under steady-state operation through modeling in RELAP5/SCDAP Mod 4.0. However, comparison of the results and validation of the model requires analyzing a benchmark SG design. For this purpose, the steam generator of the Multi-application Small Light Water Reactor (MASLWR) designed at Oregon State University has been selected as a benchmark.

What follows is a description of the proposed SG design, the reference SG design and the methodology adopted in the present work given in section II. Section II.A provides details of the proposed SG design. A brief overview of the MASLWR thermal-hydraulic design concept is given in section II.B. This is followed by (section II.C) a description of the RELAP5 model of the steam generator. Results are presented in section III. Accomplishment of the steady-state and validation of the model are discussed in section II.A. Steady-state thermal-hydraulic performance of the steam generator is presented in section II.B. Conclusions are given in section IV.

II. Materials and Methods

The work described in this paper deals with an innovative design of steam generator for integral type SMRs. Thermal-hydraulic behavior of the proposed design is analyzed through modeling in RELAP5/SCDAP Mod 4.0. For compassion of the results, steam generator of the natural circulation based Multi-application Small Light Water Reactor (MSLWR) has been selected as a reference.

II.A. Proposed Steam Generator Design

The proposed steam generator design is for integral type reactors. In these reactors, annular space between riser and wall of the RPV is used for steam generator. Primary focus of the present work is to develop a simplified steam generator design that possesses the following traits:

a) Efficient in heat transfer

b) Robust again steam side instabilities

The proposed design consists of integrated units made from Inconel 690 to allow alternative annular regions for primary and secondary coolants as shown in figures 1 and 2. The annuli thus formed are connected with each other to provide strength against steam side instabilities. However, as primary coolant pressure is higher than secondary coolant, secondary side annular regions are vulnerable against collapsing. This is prevented by inserting corrugated strips in the secondary side annuli. Such strips are shown in figure 3. The secondary side annular regions are thus divided into corrugated square channels. This serves to enhance heat transfer as well. The feed water introduced from headers at the bottom rises in secondary side corrugated channels. Steam is collected from headers on the top.

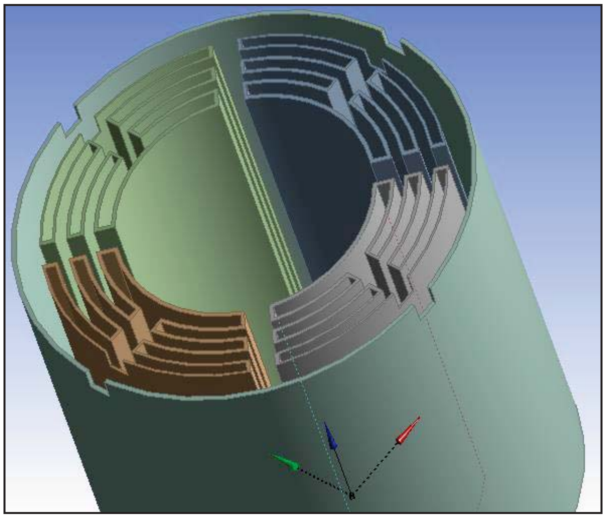

Figure 1: Isometric view of the proposed steam generator design

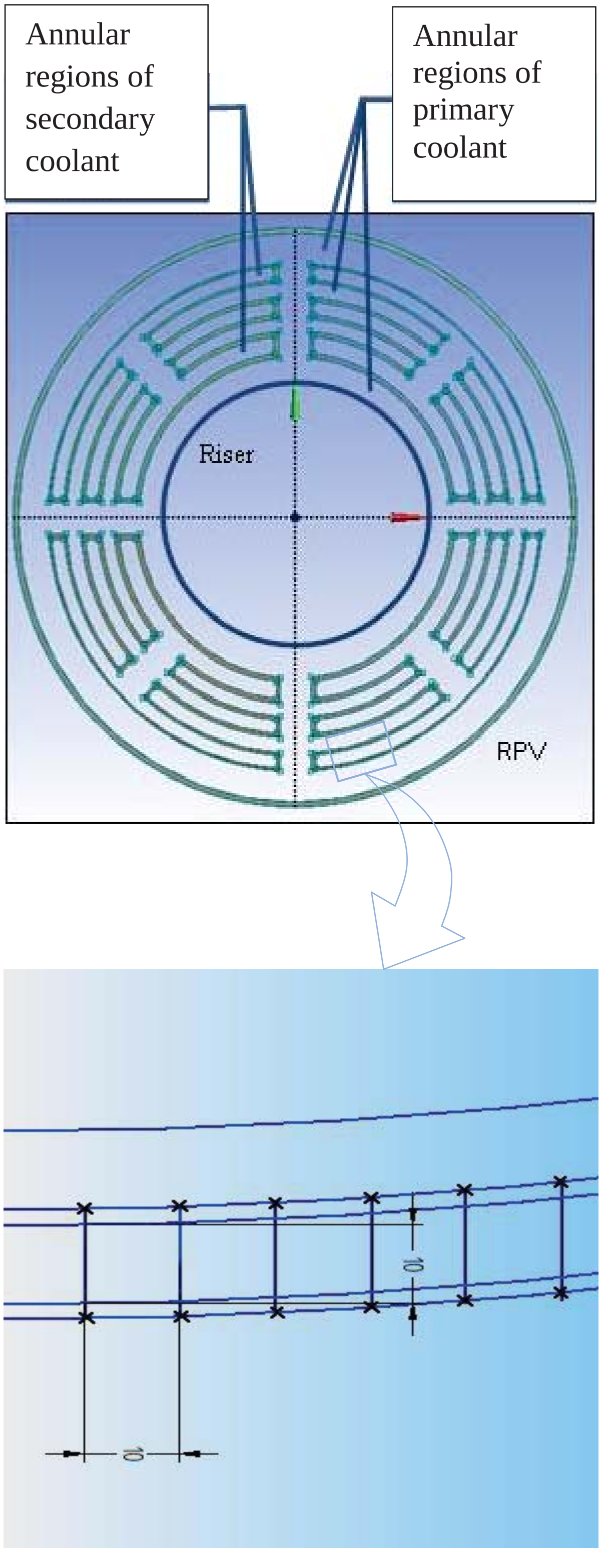

Figure 2: cross-sectional view of the proposed steam generator design

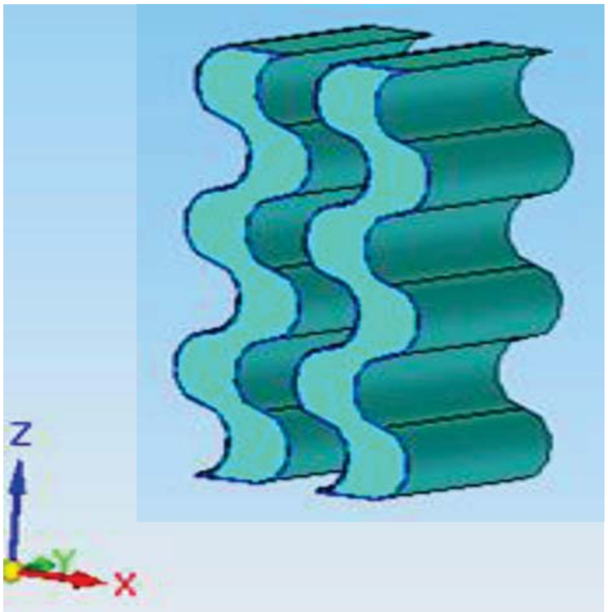

Figure 3: Corrugated strips inserted inside the secondary annular regions

For thermal-hydraulic analysis of the proposed steam generator design, thickness of primary coolant annuli is considered to be 10 mm. The thickness of the wall separating primary and secondary fluid is taken as 2.0 mm. Secondary side is considered to be consisting of flow channels 10 mm by 10 mm in cross-section. The length of secondary channel depends on the radius of curvature of corrugated strip. For comparison purpose, the length of channel has been taken equal to tube length. The mechanical analysis of the proposed design is left for future work.

II.B. Description of the Reference Steam Generator

The Multi-Application Small Light Water Reactor (MASLWR) is developed by the Oregon State University and Idaho National Engineering and the Environmental Laboratory (INEEL). It is a small natural circulation based modular pressurized water reactor having a net output capacity of 35 MWe (150 MWt).

The MASLWR incorporates an integrated reactor pressure vessel (RPV) housing a helical coil steam generator above the reactor core in an annular region between riser and wall of the RPV. The steam generator is a once-through helical-tube type consisting of 1012 tubes made of thermally treated Inconel 690. Each tube has an outside diameter of 16 mm and a wall thickness of 0.9 mm. The average length of tubes is 22.3 m. These tubes are divided into two bundles; both are arranged in upwardly spiraling pattern but in opposite sense. Hydraulic expansion and welding technique has been used to connect SG tubes to tube sheets. The arrangement of tubes is such that it casts a square pitch; with a transverse pitch ratio of 1.8 and a vertical pitch ratio of 1.5. Cold feed water at a lower pressure enters into tubes at the bottom of steam generator. Steam is produced inside tube as a result of boiling. On further moving along the length of tube, steam gets superheated which is finally collected at the top.

II.C. Development of the RELAP Model

The simulation code used in this work is the RELAP5/SCDAP Mod 4.0 developed as a part of International Development and Training Program (SDTP). The first step of simulation is division of the entire system into nodes (called nodalization). Nodes in RELAP5 represent hydrodynamic components and heat structures. The steam generator of MASLWR is divided into several nodes as shown in figure 5.

The part of secondary side that has been modeled consists of SG inlet, SG coiled-tube section, and SG outlet. Time dependent volumes are placed at inlet and exit of SG tube side to provide boundary conditions. As shown in Figure 5, the inlet boundary conditions are modeled by time dependent volume (110) whereas control of inlet temperature, pressure, and mass-flow rate are provided by a time dependent junction (120). The flow then enters into the PIPE 125, which represents steam generator channels. The single volumes (122 and 128) prior and after the PIPE 125 model the feed-water inlet and steam outlet respectively. The steam is finally dumped to the TDV 130.

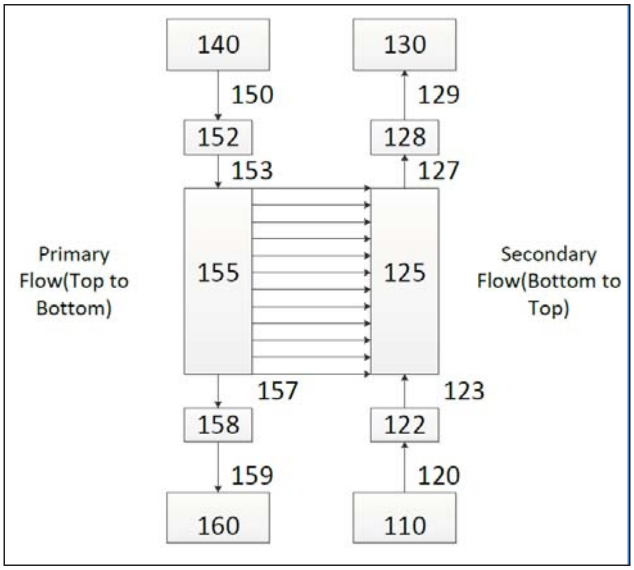

Figure 5: Primary and secondary systems nodalization diagram of the MASLWR steam generator

The section of primary loop modeled is also shown in figure 5. The boundary conditions are applied at the inlet and outlet by time dependent volumes (TDV) 140 and 160. At the inlet section of steam generator shell, a constant flow rate is maintained through the time dependent junction 150. This junction connects the TDV 140 to the single volume 152. The SG shell side is modeled by the pipe component (155). The SG shell is connected to the single volume 158 (SG outlet) through the single junction 157. The SG outlet is connected to the sink (TDV 160) through the single junction 159.

The thermal interface between primary and secondary side is modeled through heat structure. The primary system is connected to outer (right) side of heat structure whereas the secondary side is connected to inner (left) side of the heat structure. The heat structure is divided into 10 axial sub-volumes and three radial mesh points.

III. Results and Discussion

The steady-state thermal-hydraulic behavior of the proposed steam generator design and the MASLWR steam generator has been studied using RELAP5/SCDAP Mod 4.0. The results of the analysis are presented here in this section.

III.A. Accomplishment of the Steady-state and Model Validation

In order to simulate the MASLWR steam generator using RELAP5/SCDAP Mod 4.0, the first step is to achieve steady-state operating conditions and to validate the model against conditions representing steady-state operation. Simulation was run for 300 seconds to verify that system has achieved steady-state. Figures 6 and 7 show the flow rate of the primary/secondary systems and the steam generator inlet/out temperature as a function of time. Steady-state is achieved when the system parameters remain invariant with time. From the above mentioned figures, it can be seen that steady-state has been achieved shortly after the start of the simulation.

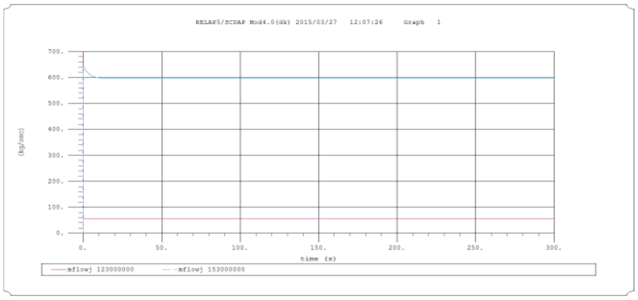

Fig.6: Primary and secondary flow rates with respect to time

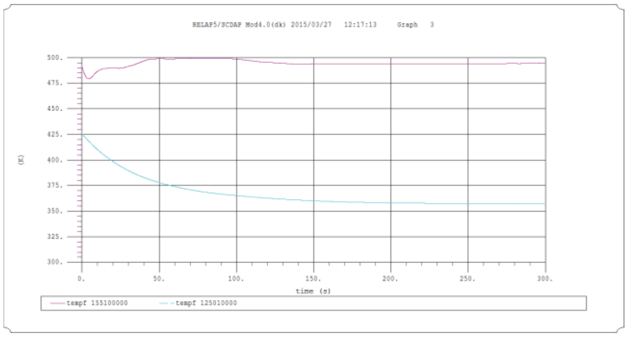

Fig.7: Steam generator inlet and outlet temperature with respect to time

Table 1 compares the RELAP computed steady-state results with the reference values. It is found that the model predicted results are in good agreement with the reference results. This validates that the model is adequate to simulate the MASLWR steam generator.

Table 1: Comparison of the code computed steady-state operating conditions with the reference values

Parameter	**Reference Value[13]**	**RELAP Value**
Primary pressure (MPa)	7.80	7.82
Primary coolant mass flow rate (kg/sec)	596	595.93
SG-shell outlet temperature (K)	491.8	491.37
SG-shell inlet temperature (K)	544.4	545.02
Secondary pressure (MPa)	1.38	1.38
Feed water flow rate (kg/sec)	56	56
Feed water inlet temperature (K)	306.4	306.4
Steam outlet temperature (K) (turbine throttle conditions)	477.0	473.0

III.B. Steam Generator Performance Analysis

After achieving steady-state, performance analysis of the proposed steam generator has been carried out. The results are compared with that of the MASLWR steam generator design. The primary side temperature profile along the length of the SG shell side is shown in figure 8.

The temperature of primary side decreases monotonically from inlet to exit. The temperature profile of secondary fluid along the channel length is shown in figure 9. It is evident from the figure that temperature of secondary fluid initially increases quickly to saturation temperature. The temperature doesn't change further during the phase change. From secondary side fluid temperature, it is evident that in the MASLWR SG, the steam temperature has started rising earlier than that of the proposed design. This implies that complete phase change in case of the proposed design occurs a little later in the channel. This inference is supported by equilibrium quality for the two designs as shown in figure 10. The vapor phase is considered when equilibrium quality attains the value 0.8. Equilibrium quality of the MASLWR SG crosses this mark earlier than that of the proposed design.

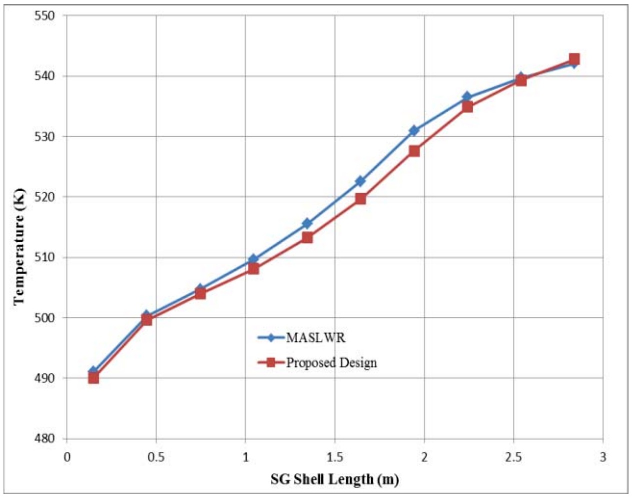

Figure 8: Comparison of the MASLWR and the proposed steam generator primary side temperature profiles under steady-state operating conditions.

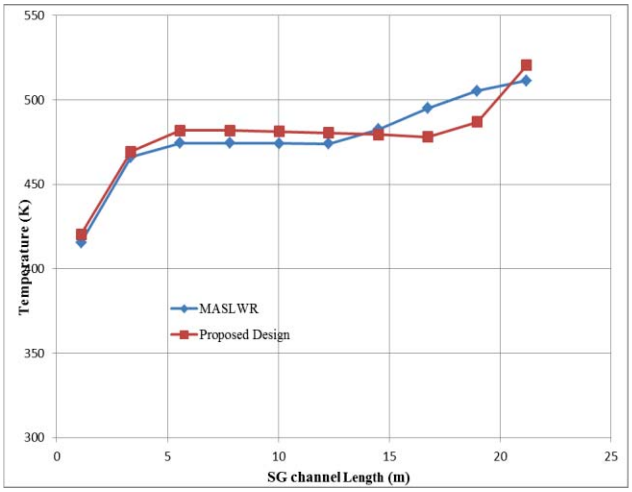

Figure 9: Comparison of the MASLWR and the proposed steam generator secondary side temperature profiles under steady-state operating conditions.

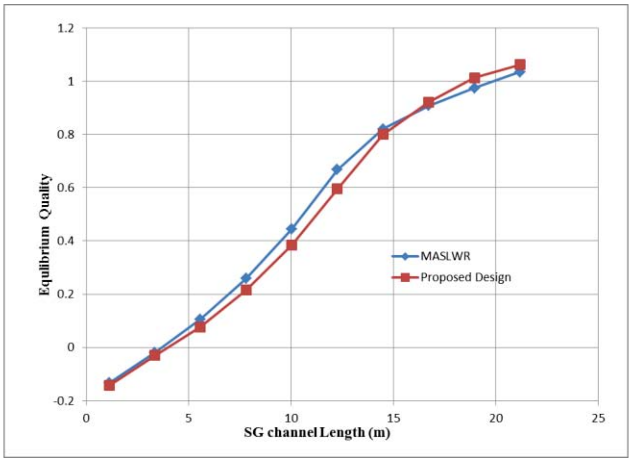

Figure 10: Comparison of the MASLWR and the proposed steam generator equilibrium quality profiles under steady-state operating conditions.

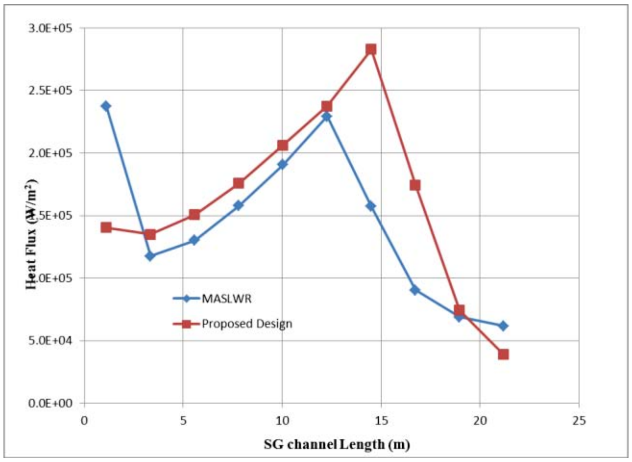

Figure 11: Comparison of the MASLWR and the proposed steam generator heat flux under steady-state operating conditions.

The thermal heat flux through channel wall of the MASLWR steam generator and the proposed steam generator design is shown in figure 11. It is obvious from the figure that heat flux through wall of the proposed design is higher than that of the MASLWR SG tube wall. This is due to less heat transfer area in case of the proposed design. It consists of rectangular channels where heat is transferred from the two outer faces only.

From these results, it is evident that overall heat transfer characteristics of the proposed design are comparable to that of MASLWR SG. However, being comprised of integrated units, the proposed design has benefit of robustness against steam side instabilities.

IV. CONCLUSIONS

A new steam generator design for integral SMRs has been proposed in this work. Thermal hydraulic analysis of the proposed design has been carried out using RELAP5/SCDAP Mod 4.0. The results are compared with helical-coiled steam generators being used in the integral SMRs. It is found from analysis that the proposed design has heat transfer characteristics comparable to the helical steam generator. However, being composed of integrated units, the proposed design has the benefit of robustness against steam side instabilities.

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