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Original Article

Steam generator performance improvements for integral small modular reactors

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A B S T R A C T

Background: Steam generator (SG) is one of the significant components in the nuclear steam supply system. A variety of SGs have been designed and used in nuclear reactor systems. Every SG has advantages and disadvantages. A brief account of some of the existing SG designs is presented in this study. A high surface to volume ratio of a SG is required in small modular reactors to occupy the least space. In this paper, performance improvement for SGs of integral small modular reactor is proposed.
Aims/Methods: For this purpose, cross-grooved microfins have been incorporated on the inner surface of the helical tube to enhance heat transfer. The primary objective of this work is to investigate thermal–hydraulic behavior of the proposed improvements through modeling in RELAP5-3D.
Results and Conclusions: The results are compared with helical-coiled SGs being used in IRIS (International Reactor Innovative and Secure). The results show that the tube length reduces up to 11.56% keeping thermal and hydraulic conditions fixed. In the case of fixed size, the steam outlet temperature increases from 590.1 K to 597.0 K and the capability of power transfer from primary to secondary also increases. However, these advantages are associated with some extra pressure drop, which has to be compensated.

1. Introduction

Advanced technologies are required to be implemented for long-term deployment of nuclear power plants to meet future energy challenges. Extensive research is being carried out worldwide for the development of innovative advanced reactors with salient features of simplified technology, inherit passive safety, sustainability and reliability, proliferation resistance, and economic viability. About 50 concepts and designs of advanced reactors 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 reactors can be found in references [1–6].

Steam generator (SG) is one of the major and particularly significant components in the nuclear steam supply system of a nuclear reactor. It is a heat sink for the reactor core. The reactor coolant flows in a closed loop through the reactor and the SG. It takes heat while passing through the core, and then flows through the SG, where it transfers heat to the secondary side coolant. When the feedwater absorbs sufficient heat, it starts to boil and form steam. Thus, the function of SGs is heat transfer from the primary cooling system to the secondary side and production of high-quality superheated steam.

Over time, a variety of SGs have been designed and used in nuclear reactor systems; some of the existing SG designs are described in Section 2. However, it is still required to make the SG more compact particularly for application in integral small modular reactors (SMRs). In this paper, a new SG design for integral SMRs with better heat transfer characteristics is proposed. The primary objective of the present work is to investigate thermal–hydraulic behavior of the proposed design under steady-state operation through modeling in RELAP5-3D. However, comparison of the results and validation of the model requires analyzing a benchmark SG design. For this purpose, the SG of the IRIS (International Reactor Innovative and Secure) has been selected as a benchmark.

What follows is a brief account of some of the existing SGs in Section 2. A short review of the enhanced boiling surfaces is presented in Section 3. Section 4 deals with the description of the proposed SG design. The reference SG design is given in Section 5. Section 6 describes the RELAP5-3D model of the SG and its

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validation. Results and discussion are presented in Section 7. Section 8 covers the main conclusions.

2. Existing SGs

Several types of SGs are currently in use in the nuclear industry. These are classified based on flow arrangement (once through or recirculation), orientation of SG (vertical, horizontal), and tube shape (straight, helical, bayonet, or U tube). Some of the important types are briefly described in the following subsections.

2.1. Once-through straight tube SGs

In these types of SGs, the coolant makes a single run and leaves the SG. The flow is in a countercurrent direction; however, SG orientation could be horizontal or vertical.

The vertical once-through straight tube SG is a straight tube counterflow SG. In this design, the primary coolant flows through the inside of the tubes vertically downward, whereas the feedwater rises upward around the tubes. By taking sensible heat, the secondary coolant changes phase and exits as superheated steam at the outlet. The Westinghouse SMR uses a straight tube SG with an external steam separating drum as shown in Fig. 1. In this design, the primary coolant flows vertically downward through the tubes whereas the secondary flow rises in the shell side taking sensible heat and finally steam is produced and directed toward steam drum for moisture separation [8].

The horizontal once-through SG is housed in a horizontal cylindrical vessel. The steam is separated and dried by gravity at the top of the housing. Horizontal SGs are considered to be more robust than vertical SGs [7].

2.2. Recirculation SGs

The recirculation SG is the most commonly used SG design in pressurized water reactors. It uses vertical U-tube bundle such that hot primary coolant flows through inside of the U tubes, whereas feedwater flows around outside of the tubes.

The Westinghouse and Combustion Engineering recirculation SGs are shown in Figs. 2 and 3, respectively. In both designs, water from the steam separators mixes with the main stream secondary coolant and rises over the U-tube bundle as it is partially converted to steam. The steam–water mixture passes through multiple levels of steam separation equipment, which returns the water to the U-tube bundle for further heating and evaporation. SGs provided by pressurized water reactor vendors differ slightly in their designs and operations. The process of moisture separation and steam drier is so efficient that the water content in the outlet steam is less 0.25% [7].

2.3. Multilayer tube SGs

A specific example of multilayer tube SGs is a bayonet tube SG. It has been used in the scaled-down reactor ALFRED (Advanced Lead-cooled Fast Reactor European Demonstrator). It is comprised of a large number of bayonet tubes arranged in a prismatic array immersed in the lead vessel pool. The construction of a single bayonet tube is shown in Fig. 4. It consists of four vertical coaxial tubes. The feedwater descends through the innermost tube (the slave tube), which is insulated from the surrounding tube (inner tube) with a strongly insulating material to get the required degree

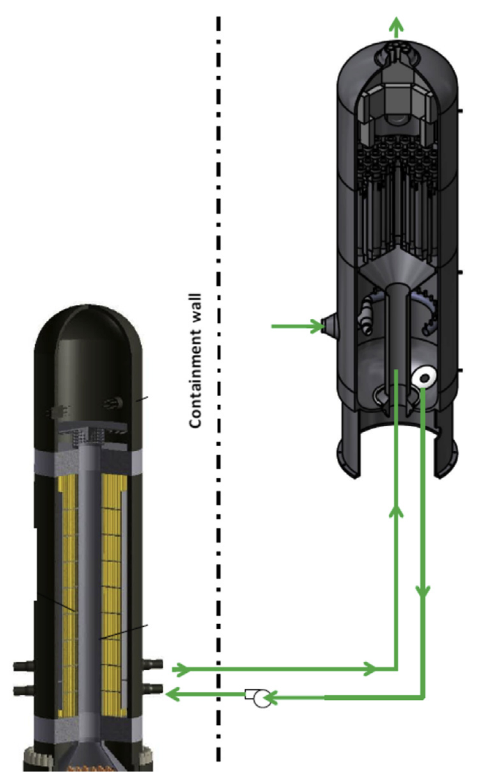

Fig. 1. Westinghouse SMR vertical once-through steam generator. SMR, integral small modular reactor. Note. From “An overview of the Westinghouse small modular reactor,” by R.J. Fetterman, A. Harkness, M. Smith, C. Taylor, 2011, Proceedings of the ASME 2011 Small Modular Reactors Symposium SMR 2011, Washington, DC, USA, American Society of Mechanical Engineers. Copyright © 2011 by ASME. With permission.

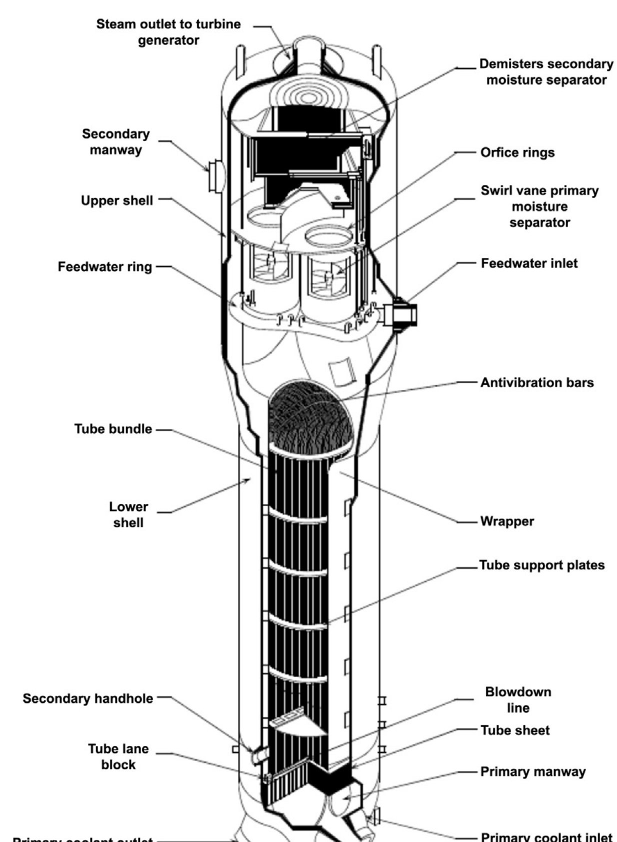

Fig. 2. Cutaway view of Westinghouse steam generator. *Note.* From: “Pressurized Water Reactor (PWR) Systems,” in Reactor Concepts Manual, USNRC Technical Training Center. Copyright by USNRC. With permission.

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