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Numerical analysis of the flow behavior in a helically coiled once through steam generator

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A R T I C L E I N F O

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A B S T R A C T

The once-through steam generator (OTSG) is an essential equipment with a key position in the primary side and the secondary side usually used in small modular reactors. It is valuable for designers of the OTSG to investigate the flow behavior in the primary side. A three-dimensional (3D) computational fluid dynamics (CFD) model is conducted in this paper to study the flow behaviors in the primary side of OTSG. The unstructured polyhedral meshes were used in this paper, and ANSYS FLUENT was the solving tool to solve the governing equations by using Realizable $k-\varepsilon$ turbulence model with enhanced wall treatment. Through a series of cases, the velocity profiles and pressure drop through the primary side of the OTSG were calculated, and the influences of different inlet parameters and different structure designs on the coolant behaviors and flow distributions were studied. Ultimately some suggestions for improvements were proposed to achieve a more rational design with more uniform flow distributions and smaller pressure drops. It was found that the flow distribution in the primary side of an OTSG is a property of its structure, on which inlet conditions have little effect. The position of inlet nozzle has a significant impact on the flow distribution.

1. Introduction

Small modular reactors (SMRs) – nuclear power plants with a capacity of less than 300 megawatts – could provide an alternative to large nuclear power plants in the future due to their safety performances, flexible and adaptable applications, multi-purpose applications and other advantages. The steam generator is an important equipment connecting the primary side with the secondary side of a nuclear power plant. Once-through steam generator (OTSG) is adopted in the majority of SMR designs due to its compactness and high efficiency [1].

KLT-40 s is an SMR designed and constructed by OKBM Afrikantov with a helically coiled OTSG, the schematic diagram of the OTSG is shown in Fig. 1. This type of helically coiled OTSG has a compact structure, enhanced heat transfer rate, higher safety, and reliability. As is shown in Fig. 1, the primary coolant enters the OTSG from the inner tube of the tube-in-tube nozzle, goes upward through the ring-shape tunnel, makes a U-turn at the top, goes downward passing the external surface of helical tubes and transfers heat to the secondary side, when the coolant reaches the bottom of the OTSG, it makes a U-turn again. Then the coolant flows through the annular space between the vessel and in-vessel baffles and exits through the outer tube of the tube-in-tube nozzle [2]. This type of OTSG is commonly used in nuclear and other industries. As the coolant flow path in the primary side looks like the English word ‘C’, we define this type of OTSG with a C shape primary flow path as C-type OTSG (COTSG).

In a COTSG, the coolant of the secondary side flows inside the helical tubes while which of the primary side flows outside the helical tubes. The fluid behaviors, including pressure drops and flow distribution, especially the flow distribution, of the primary side in the COTSG has a great impact on the heat transfer efficiency and flow stability of the steam generator. Hence, it is necessary to study flow behaviors of coolant in the primary side and verify the uniformity of flow distribution in the COTSG.

There are extensive experimental and CFD simulation studies on the process of design and thermal-hydraulic analysis of the steam generator in nuclear power plants. However, the majority of the literature focused on U-tube steam generators (UTSGs). Boyd et al. used CFD method to investigate the coolant flow behaviors in the inlet plenum during a severe accident scenario in a UTSG. The model was created for 1/7 scale of the steam generator with $k-\varepsilon$ turbulence model [3]. Reza Ghafouri-Azar developed a CFD model to test the effects of flow behaviors in CANDU steam generator. By using k-w turbulence model, he calculated the flow parameters in the lower plenum and varied the inlet tube size and locations to explore the effect of turbulence on coolant

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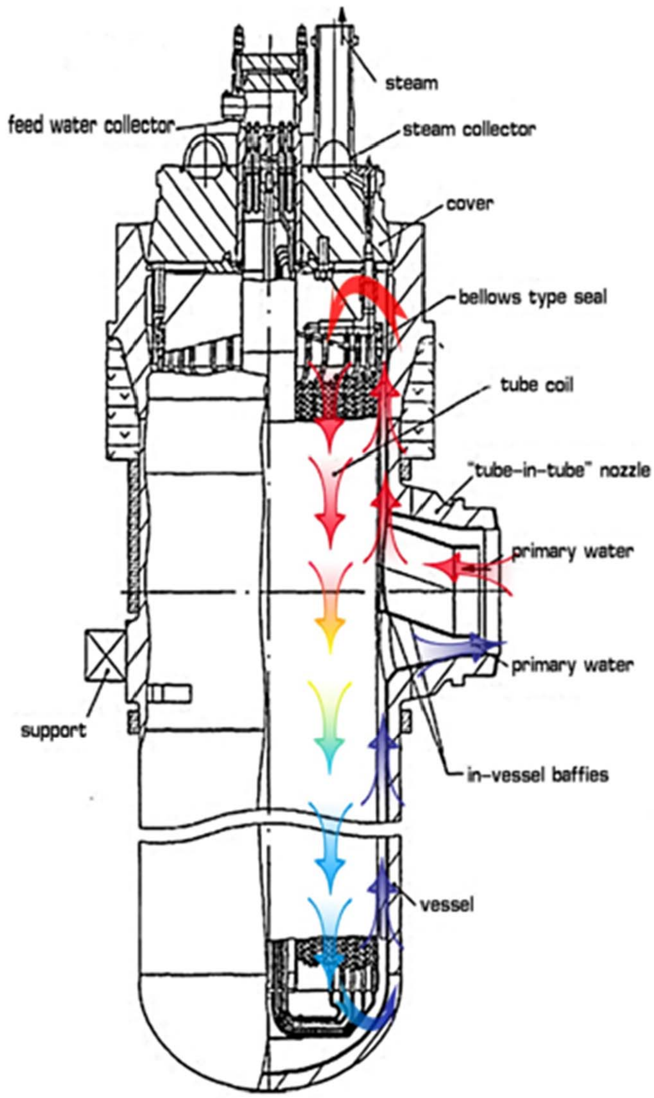

Fig. 1. The structure of COTSG in KLT-40s [2].

flow [4]. A. Dehbi and H. Badreddine proposed CFD prediction of primary flow mixing in a UTSG. A comparison between full geometry and porous medium approaches has been investigated, and the adequacy of the porous medium was validated by performing a series of simulations [5].

There are some papers focused more on the flow behavior and the mechanism of the heat transfer process in the heat transfer tube. Choi et al. used CFD method to simulate the laminar flows in helical coil tubes and investigated the phenomenon of secondary flow [6]. And Ebrahim Ahmadloo et al. numerically studied the laminar flow in the coiled hollow dust by varying Reynolds numbers [7]. They found that centrifugal force and acceleration force lead to a high velocity and pressure region at the outer side of the hollow helical pipe walls, and the CFD results are consistent with the experimental data. Computational results were obtained for heat transfer in curved pipes, representative of helically coiled heat exchangers by Piazza and Ciofalo [8]. The comparison of alternative turbulence models showed that the SST k-ω eddy viscosity/eddy diffusivity model and the second order Reynolds Stress-ω model give comparable results for the Nusselt number.

The other papers focused on the pressure losses and heat transfer in helical tube bundle. Haskins et al. [9] numerically analyzed the friction pressure losses of isothermal flows on the shell side of annular heat exchangers with helically coiled concentric tubes. Rivas and Rojas [10] simulated heat transfer of helical-coil tube bundle in molten salt using CFD method, and the correlation of heat transfer between molten salt and helical-coil tube bundle caused by natural convection was developed. Haomin Yuan et al. [11] investigated the flow-induced vibration in a helical coil steam generator experiment conducted at Argonne National Laboratory using fluid dynamics analysis code Nek5000 and structural simulation code DIABLO. it appears that below the critical velocity, the response of the tubes can be simulated with good accuracy, while above the critical velocity, the tube/flow interaction appears to require a two-way coupled model.

The research on the behavior of primary flow in the COTSG is limited. The reason is that (1) OTSG is not as widely used as UTSG and is still under development, (2) The huge computational domain and its complex geometry lead to the need for relatively large calculation resources to perform a CFD research on it. Nowadays, the researches on SMRs are becoming more and more popular. With the rapid development of computer technology, it becomes possible to build a full-scale numerical model of the COTSG. The calculation results of CFD method can provide with validation reference and guidance for the design process of COTSG, as the cost of such a full-scale experimental research is impractical due to the limitation of experimental conditions. So it is meaningful to use numerical tools to study the correlations between flow behaviors and the structure of COTSG.

This paper intends to build on the fundamental understanding of fluid behaviors and tries to find out the correlations between the structure of the steam generator and flow behavior in the primary side. Using computational fluid dynamics method, an entire numerical model has been created and the velocity profiles and pressure drop through the primary side of steam generator can be attained. The CFD results are available to achieve a more rational structure design of COTSG. Through a series of cases, the influence of nozzle position and nozzle type in the flow distribution and pressure drop of the primary side of the COTSG has been tested. Moreover, the impact of the different inlet parameters, including mass flow rate and temperature, on flow field is also being discussed. Ultimately, the insight is obtained into the importance of various modeling considerations in a model with such a complicated structure and large-scale grids, and some suggestions for improvement of the structure design will be discussed.

2. Methodology

2.1. Physical model

Fig. 2 shows a full-scale geometry model of the flow passage in a COTSG with the same type of structure of the OTSG in KLT-40s, which is taken as studying object in this paper. The height of the COTSG is 6.7 m, and the diameter is 2.3 m. There are 474 helically coil heat transfer tubes in the downward cavity of the steam generator, which is designed to remove the heat of coolant and employ the once-through concept to produce dry, superheated steam at the outlets of the steam generator.

There have been some assumptions made in this research:

(a) The COTSG was operating at steady-state
(b) Porous media with parameters calculated from empirical formula was used to simulate the pressure drop of the primary flow in the tube bank. Because the main focus of the current study is on the flow distribution and pressure drops of the whole COTSG, and the detail of the primary flow in the tube bank is not the main concern of this research, therefore, the simplification of tube bank is reasonable.
(c) The flow of primary side was regarded as a liquid with the constant property, for the temperature differences in the primary side are small enough to be considered as negligible in our COTSG design.