International Journal of Heat and Mass Transfer 94 (2016) 211–221

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

The optimum design and arrangement of a steam generator in an integral pressurized water reactor

Xinyu Wei [a,*], Chunhui Dai [b], Pengfei Wang [a], Fuyu Zhao [a]

[a] Department of Nuclear Science and Technology, Xi'an Jiaotong University, Xi'an, Shaanxi 710049, PR China
[b] Lab. on Steam Power System, Wuhan Second Ship Des. & Rec. Institute, Wuhan, Hubei 430064, PR China

ARTICLE INFO

Article history:
Received 4 June 2015
Received in revised form 10 November 2015
Accepted 19 November 2015

Keywords:
Double-tube once-through steam generator (DOTSG)
Pitch
Arrangement
Two-level optimization method

ABSTRACT

This paper presents a double-tube once-through steam generator (DOTSG), whose tube unit includes an outer straight tube and an inner helical tube, in an integral pressurized water reactor (IPWR). To obtain the optimum structure of the inner helical tube and the arrangement of DOTSGs in the reactor pressure vessel, a two-level optimization method is used, aiming at the lower pumping power needed, and a smaller reactor pressure vessel volume is used. The pitch of inner helical tubes and the central distance of outer tubes are considered design parameters when minimizing the pumping power with the genetic algorithm in the bottom level, while the number of tube units in a single DOTSG and the number of DOTSGs in the reactor pressure vessel (RPV) are optimized to obtain the minimum volume of the IPWR, which is conducted in the top level. The optimum pitch of the helical tube varies in the sub-cooled region, boiling region and superheated region. The results show that the smaller pitch brings a shorter tube length and a higher pressure drop, and the effects are strong in the sub-cooled region and the superheated region but weak in the boiling region. In this way, the optimal structure of the inner helical tube is a small pitch in the single-phase region and a large pitch in the boiling region. According to the bottom level results, the optimum arrangement of DOTSGs in the pressure vessel is determined.

1. Introduction

The integral pressure water reactor (iPWR) has advantages in the aspects of volume, weight, cost, and safety, which make it has been widely used in nuclear engineering, such as nuclear power propelling, heat supply, seawater desalination and integrated nuclear power station of next generation [1–4]. In iPWR, the main equipment of the primary loop system, including reactor core, steam generators, main coolant pump, and pressurizer, is housed in the reactor pressure vessel (RPV). This compact structure eliminates the pipe connection and essentially excludes the occurrence of large break loss of coolant accidents (LBLOCA). The compactness and thermal hydraulic characteristics of the once-through steam generator (OTSG), that transfers heat from the primary side to secondary side and supplies superheated steam to the turbine, contribute a lot to the advantages of iPWR, such as simple mechanical structure, smaller size, and higher heat transfer efficiency. So, the OTSG is one of the most widely used stream generator in iPWR [5–8].

This paper presents a double-tube once-through steam generator (DOTSG) whose tube unit includes an outer straight tube and an inner helical tube, which is showed in Fig. 1. The DOTSG adopts a vertical, counterflow, shell-and-tube heat exchanger, which is an existing double tube type heat transfer structure [9,10].

In the primary side, water flows through the inner helical tube and the shell side, while in the secondary side water/steam flows through the lunate channel between the outer straight tube and the inner helical tube. In the both sides of the inner helical tube, the flow is spirally, therefore, the heat transfer is enhanced, and this is the first advantage of the inner helical tube. The osculating structure of the helical tube and the outer straight tube reduces the tube vibration, and this is the secondary advantage. But the helical tube results in the additional flow resistance.

In RPV, a certain number of units constitute a DOTSG and a certain number of DOTSGs are located around and above the reactor core. The structure, size, and arrangement of the tube units and DOTSGs in the RPV are key factors to the size of the whole iPWR. In order to design an iPWR with compact structure, the choice of an appropriate design parameter is considered as an optimization problem and solved by the two-level optimization method in this study.

* Corresponding author. Tel.: +86 13772096784 (cell), +86 029 82668648 (o).
E-mail addresses: xyuwei@mail.xjtu.edu.cn (X. Wei), 24659300@qq.com (C. Dai), pengfeixiaoli@yahoo.cn (P. Wang), fuyuzhao_xj@163.com (F. Zhao).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2015.11.070
0017-9310/

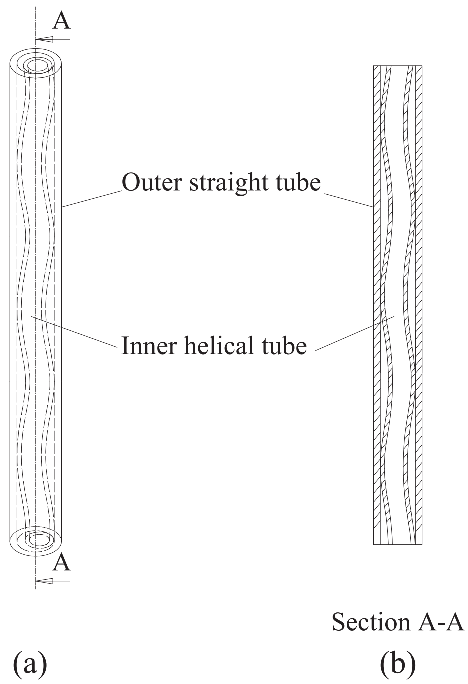

Fig. 1. The structure of tube unit of DOTSG. (a) Perspective view, (b) axial cross section.

Many scholars have studied on the OTSG equipped in iPWR. However, most of their works studied on the thermal hydraulic characteristics [11–13], model and transient performance [14–16]. There are few researches aiming at the structure design and arrangement in the reactor pressure vessel of the OTSG.

Chen et al. [17] designed and optimized a double-tube heat exchanger. They used the smallest difference of outlet temperatures of two primary sides to appraise the best flow distribution. In order to reach the optimized flow distribution, the gap width changes with the tube dimensions. Yu and Jia [18] developed an immovable enthalpy boundary model for heat transfer calculation of the DOTSG, and their results indicated that the heat transfer was enhanced by the inner helical tube. But the pressure drop was not considered in their study. As to the optimization of the heat exchanger, some authors considered the cost of heat transfer surface area or capital investment as an objective function to be minimized [19,20], while others considered the sum of entropy generation of streams as an objective function was also reported in [21,22]. We have optimized the single tube unit of DOTSG use multi-objective optimization method and Maximum principle respectively [23,24]. However, the previous work only focus on the single tube unit. When it comes to the design of whole iPWR, the situation is different: (1) the whole heat transfer area must be calculated, that means the number of the tube units is needed to be calculated; (2) as the arrangement of DOTSGs determines the diameter of the RPV, how many DOTSGs equipped in the vessel, and how many tube units in every DOTSG should be optimized. Therefore, we propel the studies to overcome these problems. In this paper, a two-level optimization method is proposed. At the top level, the objective is to minimize the volume of the RPV, while at the bottom level, the objective is to minimize the total pressure drop of the DOTSG.

This paper is structured as follows. Sections 2 illustrate the DOTSG in iPWR, and introduces the heat transfer process and the pressure drop calculation for DOTSG. Section 3 establishes optimization problem that is optimized later by the two-level optimization method. The results are discussed in Section 4. Finally, conclusion is given in Section 5.

2. Problem formulation

We design a concept iPWR, which adopts the DOTSG as steam generator. The systematic diagram of a typical iPWR is shown in Fig. 2.

The core is located at the lower part of the RPV, and the DOTSGs are symmetrically arranged along the annular region at the upper part of the RPV. The pressurizer is located in the top of the RPV. Main coolant pumps (MCPs) are equipped above the DOTSG. Once the heat in the core is removed, the primary coolant flows upward through the upper region, and enters at the top of the DOTSGs. It then travels downward through the DOTSGs, where the heat will be transferred to the secondary coolant. Finally, the primary coolant exits at the bottom of the DOTSGs and back into the reactor core. In the secondary side, the feed water enters the bottom of the DOTSGs, then flows upward inside the thimble tube to remove the heat from the primary coolant and exits the DOTSGs as superheated steam which flows to the turbine.

Fig. 3 is the structure diagram of the DOTSGs. In the RPV, the DOTSGs are symmetrically arranged along the annular region between the core support barrel and the RPV wall. Fig. 3(a) shows the relative location of the reactor core and DOTSGs from the cross section. There is a gap between the core and DOTSGs, which is accommodated the fixed devices and accessory equipment. Fig. 3 (b) is a single DOTSG, the tube units are arranged staggered, which can make the DOTSGs and the whole iPWR more compact. The details of the staggered arrangement of tube units are showed in Fig. 3(c). It is feasible and convenient to assume that every steam generator tube has identical flow. The dashed line in Fig. 3(c) is the assuming shell side boundary of one single tube unit. It can be seen that there are three flow channel in the tube unit from Fig. 3 (c) and (d), Channel A is the primary side in the inner helical tube. Channel B is the secondary side, Channel C is the primary side in shell side. In a single tube unit of the DOTSG, the primary water flows in Channel A and C, while the secondary fluid flows in Channel B, which is constituted by the outer straight tube and the inner helical tube. The secondary fluid obtains heat from the primary water in both of the inner helical tube and shell side. Fig. 3(d) is the vertical section of the tube unit. The pitch of the inner helical tube is the axial length of one coil of the helical tube, which is denoted by S in the figure.

2.1. Reactor volume

As shown in Figs. 2 and 3(a), the volume of iPWR can be calculated by formula (1).

$$V_R = \frac{\pi}{4}\left(D_c + 2D_{sg} + 2D_d\right)^2\left(L_c + L_{sg} + L_d + L_t + L_b\right) \tag{1}$$

where D_c, D_{sg}, D_d are the diameters of reactor core and DOTSGs, and the radial gap distance between the DOTSG and reactor core. L_t is the top part height of RPV above the DOTSG, L_{sg} is the height of DOTSG, L_d is the axial distance of reactor core and DOTSG, L_c is the height of reactor core, L_b is the bottom part height of RPV under the reactor core. L_c, L_b are considered constant in this study. D_{sg} is calculated by formula (2)

$$D_{sg} = p_t \times N_d \tag{2}$$

where p_t is the central axes distance of outer tubes, N_d is the number of the tube units along the diagonal in the single DOTSG.

2.2. Heat transfer model

For the single tube unit of DOTSG, it is divided into three regions according to the secondary water/steam status: sub-cooled region, boiling region, and superheated region. In the sub-cooled and superheated regions, the secondary fluids are sub-cooled water