



## Study of perforated plate effect in horizontal WWER1000 steam generator

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### HIGHLIGHTS

- ▶ Effect of perforated plate in steam distribution at top levels of SG is studied.
- ▶ The 3D numerical model of SG is prepared in ANSYS CFX.
- ▶ The interfacial functions for mass, momentum and energy transfer are prepared.
- ▶ The desired boundary conditions and marching method are implemented.
- ▶ The void fraction values are compared with experimental data.

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### ABSTRACT

In this paper, the effect of perforated plate in horizontal steam generator (SG) has been studied. The injected feed water into the SG is cold and heavy, so it pulls down the fluid around the feed water injection pipeline. The perforated plate has been designed above tube bundles in the SG to relax this asymmetrically void generation. In this work, with consideration of the perforated plate and feed injection effects in tube side, it is illustrated that generated steam will be distributed in the top level of the SG homogeneously. Therefore, the steam collector contains high quality homogeneously distributed dry steam and the perforated plate prevents the water from ascending in the cold side containing cold collector and the steam from descending on the other side. In addition, it can be seen that without the perforated plate, the void fraction distribution becomes heterogeneous in the top level of the SG. In this analysis, the 3D numerical model of a large conventional WWER1000 steam generator in the nuclear industry has been presented. For the computational fluid dynamic (CFD) study of desired steam generator in ANSYS CFX, the SG geometry is prepared with details and interfacial relations of mass, momentum and heat transfer are defined by appropriate functions. In momentum source terms, the interfacial drag forces are defined with Ishii and Zuber model. An Euler–Euler approach is applied to modeling boiling heat transfer and condensation. Porosity model is applied to the primary side in which the tube bundles are not described in detail but they are modeled as sources of enthalpy and pressure loss. The primary side effect is modeled based on a 1D thermal heat source model. Finally, the importance of perforated plate is demonstrated and it shows that the results are in a good agreement with published and experimental data.

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### 1. Introduction

Steam generator is a heat exchanger of pressurized water reactor (PWR) that nuclear power plant (NPP) uses to evaporate the secondary side water. A steam generator (SG) has a significant role in the operation of a pressurized water reactor power plant and the prolongation of its life cycle. The steam generator not only transfers thermal energy from the primary coolant to the secondary side,

but also prevents the release of radionuclide. The preservation of the complete separation between the primary and secondary loops is very important in order to avoid radioactive contamination of secondary loop and leak of coolant, as well.

The investigations in the flow field of water and steam mixture on the secondary side of horizontal or vertical steam generator of the NPP are limited due to lack of large experimental devices, as well as the difficulties related to the measurements in the real NPPs. The two-phase flow in a complicated three-dimensional (3D) geometry is also very problematic in the field of computational fluid dynamics (CFD). Regarding importance of steam quality in power plant, the steam distribution in steam generators

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needs some detailed researches. The flow fluid studies about temperature and pressure of fluid would be very useful to manage power cycle thermal-hydraulic parameters, accident analysis and steam generator lifetime. The geometry of the secondary side of a steam generator is complicated for a detailed numerical simulation. Therefore, some simplifications are suggested with previous works. Stavanovic and Studovic (1999) have suggested using a model in which the tube bundles of the steam generator are considered as a porous media. They presented a simplified thermal-hydraulics model and a numerical procedure for the simulation and analysis of steady state nuclear power plant components. The porosity model presented by Stosic and Stevanovic (2002) simulated the secondary side of the steam generator. Groburov and Zorin (1994) reported a simple model of WWER1000 SG shell side two-phase flow within tube bundles. Kristof et al. (2008) presented the numerical model of WWER440 steam generator in fluent.

The most important effect concerning the shell side flow in a secondary boiler is the unevenness of heating (Kristof et al., 2008). The WWER1000 type steam generator contains 10,978 tubes of 16 mm diameter bent in horizontal planes delivering high temperature primary circuit water. The enthalpy of the primary circuit coolant delivered to the secondary circuit water on the shell side of the pipes to the saturation temperature eventually evaporating it. The effect of the primary circuit on the secondary side is characterized with source terms of heat. Indeed, this term makes it possible to describe the heat transfer from the primary circuit to the secondary side. In this paper, the effect of perforated plate in horizontal steam generator (SG) has been studied. The injected feed water into the SG is cold and heavy, so it pulls down the fluid around the water injection system. Without the perforated plate, the void fraction distribution becomes more heterogeneous. In this work, with consideration of the perforated plate and feed injection effects in tube side, it illustrates that generated steam is distributed in the top level of the SG homogeneously. Therefore, the steam collector contains high quality homogeneously distributed dry steam and the perforated plate prevents the water from ascending in the cold side containing cold collector and the steam from descending on the other side. In the presented simulation, a complete 3D model of the horizontal WWER1000 steam generator has been prepared. The Euler–Euler multiphase model is used in computational fluid dynamics modeling of the secondary side. Consequently, equations for mass, momentum and enthalpy conservation will be solved for two phases. The numerical model involves the relevant interactions between the phases, drag forces and the mass transfer between the phases due to evaporation and condensation. The source terms are implemented into the ANSYS CFX code by using user-defined functions. The spatial distribution of the transferred heat flux is modeled by 1D thermo-hydraulic model. This model is constructed of a pipe from the primary side of the steam generator. Solving the Navier–Stokes equations numerically, the distribution of heat flux in the pipe will be gained. The 3D steam generator CFD modeling prepared numerical results for full load operating condition. The obtained results clearly illustrated the role of submerged perforated plate in the distribution of the void fraction and pressure losses in top levels of SG. Finally, it shows that the results are in a good agreement with published and experimental data.

## 2. Model description

The role of SG in a PWR nuclear power plants is the heat transfer from the reactor cooling system, to the secondary side of the tubes containing feed water. Primary coolant receives heat passing through the core, and then flows through the steam generator, where it transfers heat to the secondary coolant water to make steam (Green and Hetsroni, 1995). Eventually, the steam drives a turbine connected to an electric generator to produce energy. The

coolant enters the hot leg from the reactor and circulates through the tube bundles of the SG and out of the cold leg into the coolant pumps suction line (Fig. 1). Heat is transferred through the wall of the tubes from the hot coolant, boils the water on the shell side, and generates steam. The feed water enters to SG just below the perforated plate and joints the water being circulated. It then flows upward by natural convection through the bundle absorbing heat, and leaves the tube bundles as a steam water mixture. The main components of the SG are (Fig. 1):

- Steam generator body
- Heat transfer tubes and primary coolant heads
- Feed water nozzle facility
- Perforated plate
- Inlet collector, outlet collector, steam collector, . . .

Feed water flows into the steam generator through a pipe 426 mm inside diameter, then through 16 collectors of 80 mm inside diameter, which are coupled to the distribution pipes. Each of these distribution pipes has 38 perforated pipes. Some are at the upper steam tubing elevation while another portion is over the perforated plate in order to balance the non-uniform steam generation. This is achieved by partial condensation of the voids in high steam areas. The perforated plate is a metal sheet with structured holes for steam ascending. The perforated plate has been designed above the tube bundles to relax asymmetrical void generation. The sheet prevents asymmetry circulation of feed water and helps to homogenous boiling of it. The design data for desired SG are shown in Table 1.

### 2.1. The ANSYS CFX model

In this work, three-dimensional model of the steam generator is modeled in ANSYS CFX, and unstructured meshes are generated for numerical calculations. The detailed 3D model consists of about 4.5 million computational cells. There are 2.8 million computational cells in the simplified 3D model. In the simplified case, some details of minor importance will be ignored in order to reduce the number of cells. Using the converged results of the simplified model as initial condition for the finally improved model, the time of computation was reduced. The 3D SG model with all meshes is shown in Fig. 2. Time dependent numerical simulation has been carried out in every case with sufficient number of time steps to obtain converged solution. Indeed, the marching method is chosen for suitable convergence of results. In addition, to access the accurate superficial velocity of water and vapor, the effect of tube bundles should be considered. For this, the 2D model in ANSYS CFX has been developed. In this case, a section in the middle of steam generator, considering all tubes, has been simulated.

## 3. Governing equations

The three dimensional CFD model used herein includes the continuity, momentum, and energy conservation equations. The general equations for the CFD analysis of the SG are defined as below (Feng, 2007; Pattikangas et al., 2010; Wang et al., 2012):

Conservation equations for phase  $q$ :

$$\text{Mass conservation : } \frac{\partial}{\partial t}(\alpha_q \rho_q) + \nabla \cdot (\alpha_q \rho_q \vec{V}_q) = S_{mass,q} \quad (1)$$

$$\text{Momentum conservation : } \frac{\partial}{\partial t}(\alpha_q \rho_q \vec{V}_q) + \nabla \cdot (\alpha_q \rho_q \vec{V}_q \vec{V}_q) = S_{M,q} \quad (2)$$

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