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Horizontal steam generator thermal hydraulic simulation in typical steady and transient conditions

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HIGHLIGHTS

- Simulation of the horizontal steam generator with the available code in typical normal and transient operations.
- Replacement of tube bundle with a porous media due to the complexity of the SG geometry.
- Simulation of typical transient mode of the VVER 440 steam generator, loss of feed water accident.

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ABSTRACT

Thermal hydraulic analysis of the steam generators as one of the main components of the power cycle in pressurized water reactor (PWR) is crucial in the design and safety of the nuclear power plants. Two phase flow field simulation near the tube bundles is important in obtaining logical numerical results however the complexity of the tube bundles due to geometry and arrangement makes the numerical analysis complicated. In this research tube bundle has been assumed as the porous media and the outlet boundary condition as the one of the main challenge in these kind of simulations has been optimized according to similar researches. In order to adjust and tune the available computational fluid dynamic (CFD) code, pressure drop of the typical kettle reboiler tube bundle in two various heat fluxes and vapor volume fraction distribution in VVER 1000 steam generator in normal operation have been investigated. The typical transient mode of the VVER 440 steam generator, loss of feed water accident, has been studied eventually. It was observed that obtained vapor volume fraction can predict experimental data with more accuracy than the similar researches and would be increased with the elevation during the accident. On the other hand, pressure drop and level of the feed water value reduces through time and show good adoption with the measurements.

1. Introduction

Unlike boiling water reactors (BWRs), pressurized water reactors (PWRs) nuclear power plants use steam generators to convert water into steam. Steam generators play significant role in the safe and reliable operation of VVER power plants. Hot radioactive water, enters the generator from the reactor and heats non-radioactive water on the outside, which makes steam. The steam is then condensed back into water for another trip through the steam generator. Steam generator thermal hydraulic simulation in normal and transient condition is helpful in improvement of power plant operation. A simplified two-fluid computer code to simulate reactor-side transients in a PWR steam generator is reported by Munshi et al. (1985). The disturbances are modeled as ramp inputs for pressure, internal energy and mass flow-rate for the primary fluid. Nematollahi and Zare (2007) and Haddad and Abbasi (2012) simulated the VVER1000 steam generator tube rupture and loss of heat sink on Bushehr nuclear power plants respectively. Although these simulations that would be performed by RELAP5/Mod3.2, shown good adoption with experiments but, could not investigate distributions of the vapor volume fraction in three dimensional mode. Because of the complexity of the steam generator tube bundles, Stosic and Stevanovic (2002) proposed one of the most complete modeling of the porous media model instead of the tube bundle and also some equations such as interfacial drag force have been reported. Bamardouf and McNeil (2009) carried out experimental and numerical studies in order to obtain a model to predict pressure drop in two phase flow, across the horizontal tube bundle. In addition to the experimental results, different correlations have been obtained for two phase flow, across the tube

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Nomenclature

C_2	inertial coefficient [m^{-1}]	t	time [s]
C_d	drag coefficient	T	temperature [K]
D	tube diameter [m]	U_f	liquid velocity [$m\ s^{-1}$]
D_b	average bubble dimeter [m]	U_g	vapor velocity [$m\ s^{-1}$]
F_{lift}	lift force [N]	α	permeability [m^2]
F_{VM}	virtual mass force [N]	φ	vapor volume fraction
g	gravitational acceleration [$m\ s^{-2}$]	ρ_f	liquid density [$kg\ m^{-3}$]
h_f	enthalpy of saturated liquid [$j\ kg^{-1}$]	ρ_g	vapor density [$kg\ m^{-3}$]
h_g	enthalpy of saturated vapor [$j\ kg^{-1}$]	μ	dynamic viscosity [Pa s]
h_{fg}	difference of enthalpy between saturated liquid and vapor [$j\ kg^{-1}$]	σ	surface tension [$N\ m^{-1}$]
L	length [m]	Δp_f	liquid tube bundle pressure drop [Pa]
$\dot{m}_{pq}$	mass flow rate between phases [$kg\ s^{-1}$]	Δp_g	vapor tube bundle pressure drop [Pa]
M_g	vapor mass flow rate [$kg\ s^{-1}$]	Γ_c	condensation mass transfer [$kg\ s^{-1}$]
P	tube bundle pitch [m]	Γ_e	evaporation mass transfer [$kg\ s^{-1}$]
$\vec{R}_{pq}$	interfacial drag force [N]	τ_c	condensation relaxing time [s]
S	source	τ_e	evaporation relaxing time [s]
		γ	porosity

bundles, in different flow regimes. Based on the available modeling and previous researches in two phase flow, a slice of the kettle reboiler flow field has been simulated with CFX software. Different outlet boundary conditions have been discussed and shown that the predicted pressure drop and vapor volume fraction distribution have good adoptions with the experimental results as well (McNeil et al., 2010, 2011). Maslovaric et al. (2014) model the kettle reboiler flow field by using porous media assumption. In this research, relations that reported by Simovic et al. (2007) have been employed.

To the best of author's knowledge, there are a few references on simulation of horizontal steam generators modeled by using porous media in typical normal and particularly transient operation. The purpose of this study is to evaluate the capability of the available CFD software in simulation of the typical steam generator loss of feed water accident by comparing the results of numerical code with the available experimental results and in the presence of appropriate boundary condition. In the current study, to properly simulate the two phase flow field, the change of flow regime, from bubble flow to churn and finally mist flow has been considered. The details of numerical algorithm that is important in such simulations, including tube bundle pressure drop, turbulence, heat and mass transfer models, are fine-tuned and explained in the following.

2. Governing equation

The flow field adjacent to tube bundle in a steam generator can be studied with a variety of techniques. In order to model the two phase flow field, averaged Navier–Stokes equations have been used with Eulerian–Eulerian approach. Detailed description of mathematical models for continuity, momentum and energy equations used in the available code (FLUENT) are stated in the following (Vafai, 2005).

- Continuity equation:

$$\frac{\partial(\gamma\alpha_q\rho_q)}{\partial t} + \nabla\cdot(\gamma\alpha_q\rho_q\vec{v}_q) = \gamma\sum_{p=1}^{n}(\dot{m}_{pq} - \dot{m}_{qp}) + \gamma S_q \quad (1)$$

In Eq. (1), subscript "q" indicates the qth phase, and n is the number of phases in the system, α_q, ρ_q, $\vec{v}_q$, are volume fraction, density and velocity vector in the qth phase, respectively. $\dot{m}_{pq}$ denotes the mass transfer from pth to qth phase, while $\dot{m}_{qp}$ is the mass transfer from qth to pth phase. S_q is the external mass source applied on the qth phase and γ is porosity coefficient of the porous media.

- Momentum equation:

$$\begin{aligned}\frac{\partial(\gamma\alpha_q\rho_q\vec{v}_q)}{\partial t} + \nabla\cdot(\gamma\alpha_q\rho_q\vec{v}_q\vec{v}_q) &= -\gamma\alpha_q\nabla p + \nabla\cdot(\gamma\bar{\bar{\tau}}_q) + \gamma\alpha_q\rho_q\vec{g} \\ &+ \gamma\sum_{p=1}^{n}(\vec{R}_{pq} + \dot{m}_{pq}\vec{v}_{pq} - \dot{m}_{qp}\vec{v}_{qp}) \\ &+ \gamma(\vec{F}_q + \vec{F}_{lift,q} + \vec{F}_{vm,q}) \\ &+ \alpha_q\left(\left(\frac{\mu}{\alpha} + \frac{C_2\rho}{2}|\vec{v}_q|\right)\vec{v}_q\right)\end{aligned} \quad (2)$$

In Eq. (2), p is pressure, $\bar{\bar{\tau}}_q$ is stress–strain tensor in the qth phase, $\vec{R}_{pq}$ is the interaction drag force between the two phases and $\vec{F}_q$, $\vec{F}_{lift,q}$ and $\vec{F}_{vm,q}$ are the external body, lift and virtual mass exchange forces, respectively and α and C_2 show the permeability and inertial coefficient of the porous media.

- Energy equation:

$$\begin{aligned}\frac{\partial(\gamma\alpha_q\rho_q h_q)}{\partial t} + \nabla\cdot(\gamma\alpha_q\rho_q\vec{v}_q h_q) &= -\gamma\alpha_q\frac{\partial p_q}{\partial t} + (\gamma\bar{\bar{\tau}}_q : \nabla\vec{v}_q) + \gamma S_q \\ &- \nabla\cdot(\gamma\vec{q}_q) + \gamma\sum_{p=1}^{n}(Q_{pq} + \dot{m}_{pq}h_{pq} \\ &- \dot{m}_{qp}h_{qp}) + Q_{sp}\end{aligned} \quad (3)$$

where h_q, S_q, Q_{pq} are the specific enthalpy of the qth phase, external heat source term and the intensity of heat exchange between the phases, respectively. h_{pq}, h_{qp} and Q_{sp} are the inter-phase enthalpies and heat transfer between porous media solid phase and each vapor and liquid phases, respectively.

2.1. Pressure drop

The correlations (4) and (5) are obtained from experiments that have been performed on tube bundle flow field by considering two phase flow multiplier (Simovic et al., 2007; Rasohin, 1980).

- Liquid phase pressure drop:

$$\Delta p_1 = Eu_1\rho_1 u_1^2(1-\varphi) \quad (4)$$

- Vapor phase pressure drop:

$$\Delta p_2 = Eu_2\rho_2 u_2^2\varphi \quad (5)$$