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A Dynamic Model of U-Tube Steam Generator for CANDU Simulation

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Abstract

A simulation model for the transient behavior of CANDU U-tube steam generator(UTSG) has been developed for application to the simulation of operational transient behavior of CANDU nuclear power plant. For application to CANDU UTSG, the design characteristics of CANDU UTSG such as Wolsong Units, feedwater inlet near the tube sheet, is approximated. For realistic prediction of thermal hydraulic behavior of and tube bundle region is divided into two separate control volumes, subcooled region and saturated region, and the variation of thermal hydraulic properties within a control volume is considered. Test results for typical CANDU operational transient case show reasonable transient behavior of steam generator and considered to be applicable to the simulation of overall plant.

1. Introduction

Appropriate simulation of nuclear power plant behavior during plant transients is important in the development of operator training simulator or in the plant performance analysis. The steam generator provides a dynamic link between the primary and secondary systems. Thus an accurate steam generator model is essential for the plant transient simulations, particularly for operational transients.

The simulation models for nuclear power plants including steam generator model require fast running capability with maintaining reasonable accuracy of the predictions. For the simulation of transient behavior of CANDU such as Wolsong Nuclear Unit 1, in addition to fast running capability, it is needed to develop a CANDU UTSG model which can account for its unique UTSG design concept such as feedwater inlet near the tube sheet. In this paper, a UTSG model for DSNP-CANDU[1], which is used for the simulation of operational transients of CANDU-6, is implemented based on the previous works[2,3] and its applicability is examined for the operational transients of Wolsong Unit 1.

2. Model Description

As shown in Fig. 1, the thermal hydraulic model of the UTSG is based on a macroscopic analysis of the control volume. The secondary side variables considered are obtained by imposing macroscopic mass and energy balances on the indicated control volumes. The secondary side is divided into six main control volumes: the downcomer, subcooled tube bundle region, saturated tube bundle region, dryer/separators, vapor dome, and saturated liquid region. The saturated liquid region,which is considered for the mathmatical completeness, represents a fixed volume of recirculated saturated liquid where thermodynamic interaction with vapor dome occurs. The downcomer is a variable control volume, which determines S/G water level with the saturated liquid region. The tube bundle region is divided into subcooled and saturated region depending on the steam quality of each region with total volume of tube bundle region conserved during transient.

For any given control volume V_k with i inlets and j oulets , conservation equations of mass and energy are given, respectively, as

$$\frac{\partial M_k}{\partial t} = V_k \frac{d\rho_k}{dt} + \rho_k \frac{dV_k}{dt} = \sum_i \dot{m}_i - \sum_j \dot{m}_j \tag{1}$$

$$\rho_k V_k \frac{dh_k}{dt} = q_k + \sum_i \dot{m}_i (h_i - h_k) - \sum_j \dot{m}_j (h_j - h_k) + V_k \frac{dP_k}{dt} \tag{2}$$

where ρ_k , V_k , h_k, P_k, q_k are average density, volume, pressure, heat addition in control volume k, respectively, and the mass flow rates and enthalpies are defined at interface between control volumes. Equations (1) and (2) are applied for each control volume to obtain mass and energy conservation equation set.

The proposed steam generator model has several simplifying assumptions : 1) uniform S/G pressure, 2) thermodynamic equilibrium, 3) linear fluid quality profile up through the tube bundle region, 4) negligible vapour production and heat transfer in the downcomer, 5) complete vapour/liquid separation by the dryers and separators. In the balance equations, the enthalpy and density of each control volume are defined at the center of control volume and the mass flow rates are defined at the path between control volumes. The variation of enthalpy within a control volume is considered for estimation of outlet enthalpy in each control volume.

The boundary conditions such as feedwater flow rate and steam flow rate to turbine are given by plant specific control logics and the downcomer mass flow rate is evaluated from UTSG overall momentum balance from downcomer through top of dryer/separator region, where the frictional and accelerational pressure drop terms are approximated with the coefficient at steady state condition. The heat transfer from primary side to secondary side is modeled by simple lumped parameter heat balance between the primary coolant, the tube wall, and the secondary flow. The primary to secondary heat transfer rate in a tube bundle region is obtained for subcooled and saturated region, separately, and thermodynamic equilibrium is assumed. Therefore, each tube bundle region is also variable control volume with time and different heat transfer correlations are applied for each region. The boundary of subcooled and saturated region is evaluated depending on the steam quality of secondary side. Considering the feedwater inlet near the tube sheet, the downcomer mass flow is to be mixed with the feedwater flow at the tube bundle inlet, and the mixing of feedwater flow and downcomer flow is assumed to occur perfectly and instantly at the tube bundle inlet. The enthalpy carried by mass flow through the subcooled tube bundle region inlet is determined as mass weight average of enthalpies of downcomer mass flow and feedwater flow.

The equations resulting from the secondary side mass and energy balances and above simplifying approximations are arranged into a system of coupled equations of the form $\underline{\underline{A}}\,\underline{x} = \underline{\underline{B}}$, where unknown vector $\underline{x}$ is composed of mass flow rates in each region and time derivative terms of downcomer volume, pressure, enthalpies of tube and dryer/separator regions. The vector $\underline{\underline{B}}$ contains boundary conditions such as main steam and feedwater flow rates, downcomer mass flow rate, and heat transfer rate. At each time step in the simulation, the unknown values of $\underline{x}$ are obtained from previous time step values explicitly.

3. Results and Discussion

To evaluate the functional capability of the present model, transient behavior of Wolsong Unit 1 UTSG has been analyzed with available plant specific data. [4,5] For the transient simulation, the present UTSG model has been incorporated with the DSNP-CANDU simulation program which has been used for transient simulation of CANDU plant heat transport system. For boundary conditions of present UTSG model, steam line model and feedwater line model have been applied with corresponding control logics, boiler level control and boiler pressure control. As typical operational power transients, arbitrary setback case shown in Fig. 2, in which reactor power is decreased from 100% F.P. to 60% F.P. with a ramp rate of 0.4%/sec, was chosen for the tests and the time dependent response of the UTSG thermalhydraulic parameters have been examined. In Fig. 3 and Fig. 4, the S/G water level and power variation with time are shown respectively for the setback case. In Fig. 3, the predicted S/G level drops with time and converges to the setpoint value, which is a function of power. Also, in Fig. 4, the S/G pressure approaches the setpoint value (4.69MPa) by the operation of bolier pressure control. The observed consistency of proposed model with plant control logics indicates that the present UTSG model predicts transient S/G thermalhydraulic behavior reasonably. The fluctuations shown in Fig. 3 and Fig. 4 are mainly due to the mismatch between UTSG outlet steam flow and feedwater flow which are governed by the plant specific control logics. Based on these simulation results, the present S/G model is thought to function reasonably for the prediction of S/G transient behavior in the mild transient such as operational power maneuvering case. Therefore, the presented model could be used as a basic model for more flexible and advanced UTSG model for real-time based CANDU type nuclear power plant simulation tool.

4. Conclusion

A steam generator model for transient simulation of the CANDU power plant which has unique design features such as different feedwater inlet location from conventional UTSG, has been developed and its functional capability has been examined and proved by applying to the typical power maneuvering transient case. However, only one simple arbitrary transient case was chosen for functional test, which means that it is needed to test the present model for more realistic cases. Also, model improvements are required to account for the integral preheater adopted in UTSG of Wolsong Units and comparisons should be made by examining quantitative predictions results against any plant specific data.

References

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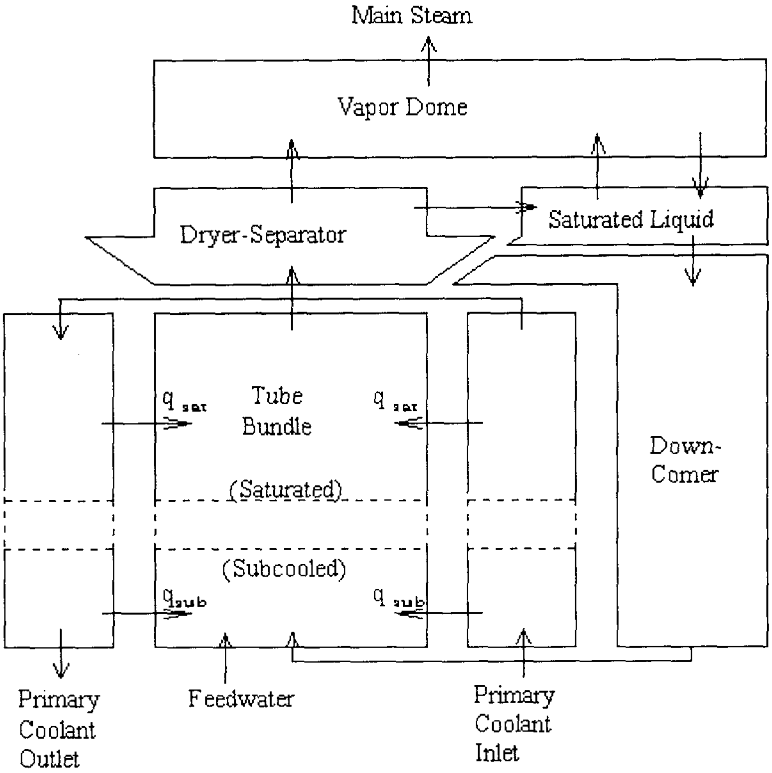

Fig. 1 Schematic of CANDU UTSG Control Volume

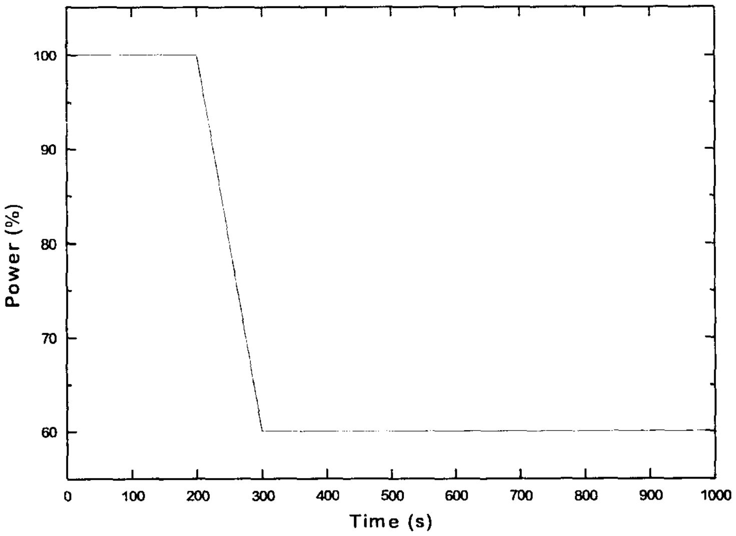

Fig. 2 Reactor Power (Set Back)

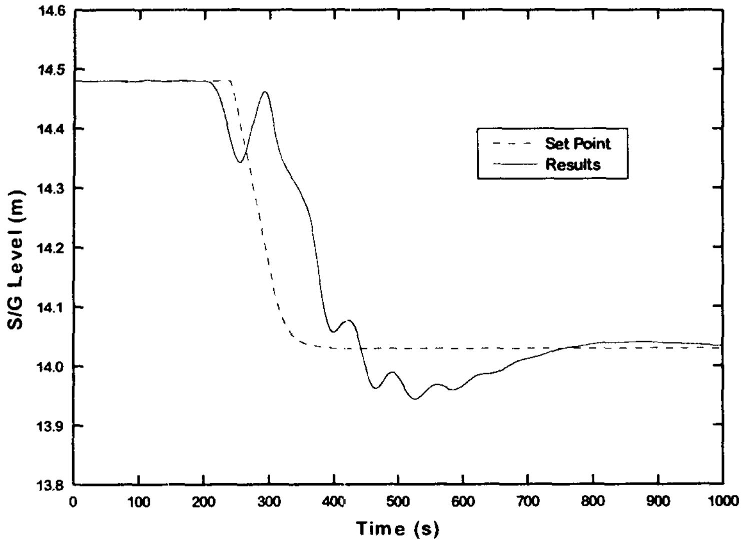

Fig. 3 Transient Behavior of CANDU UTSG Water Level

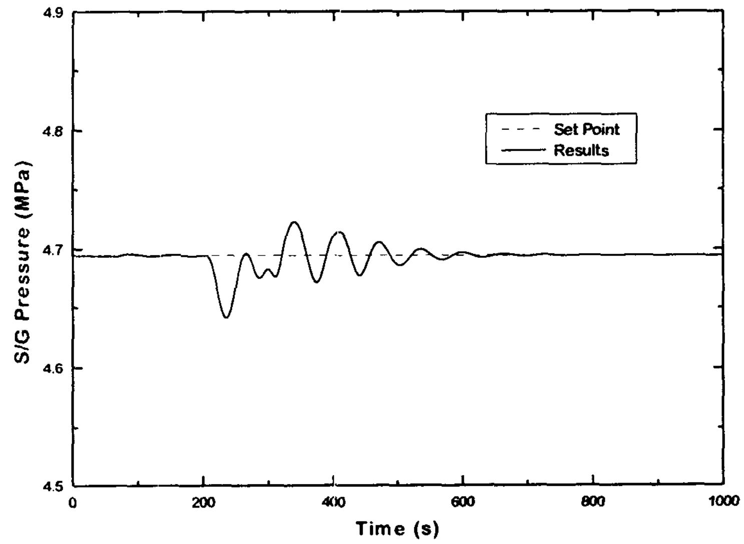

Fig. 4 Transient Behavior of CANDU UTSG Pressure