Numerical simulation of boiling and two-phase flow in PCCT of PAFS

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1. Introduction

The Passive Auxiliary Feedwater System (PAFS) is one of the passive safety features adopted in the Advanced Power Reactor Plus (APR+) and replaces the conventional active auxiliary feed-water system of the APR1400 by introducing a natural driving force mechanism (Fig. 1). It has a function of removing the decay heat and the residual heat. The PAFS is composed of two independent trains (each 100% capability) to satisfy the single failure criterion. In each train, one Passive Condensation Heat exchangers (PCHX) is installed inside the Passive Condensation Cooling Tank (PCCT) as shown in Fig. 2. The PAFS is designed to have a capability of operating without AC power or operator action for a minimum of 8 hours in 5 minutes after reactor trip and to ensure a subsequent RCS cooldown for 8 hours to shutdown cooling entry conditions.

The steam generated in the steam generator is delivered to the PCHX, and is condensed in the tube inside of PCHX. The condensate is conveyed to the economizer of the steam generator by a natural circulation system. The PCCT provides the heat sink for the PCHX. The heat addition from the PCHX initially increases the water temperature. As time passes, the water reaches saturation temperature, and then begins to boil. The steam generated in the PCCT is discharged to atmosphere. The cooling water in the PCCT circulates due to the rising steam bubbles. In process of time, the water level gets lower gradually.

The purpose of this study is to offer detailed information on thermal hydrodynamic phenomena in the PCCT of the PAFS. The thermal hydrodynamic phenomena in the PCCT are simulated using a computational fluid dynamics (CFD) technique.

2. Numerical Methods

The thermal hydrodynamic phenomena in the PCCT are simulated using a computational fluid dynamics (CFD) technique. The generation of steam bubbles on the outer surfaces of the PCHX tubes is modeled using a phase change heat/mass transfer approach. Also, two-phase flow (gas-liquid) of the generated steam bubbles and cooling water is simulated using an explicit VOF (Volume Of Fluid) model.

Three-dimensional geometric model of the PCCT and PCHX is generated based on the current design drawings.

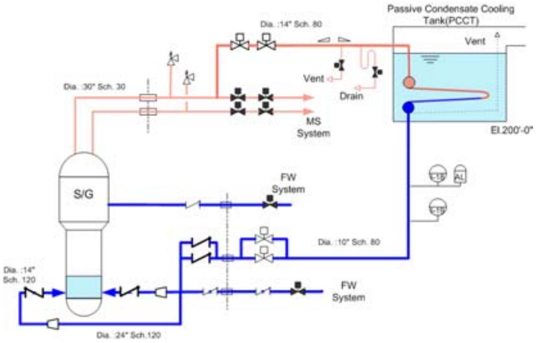

Fig. 1 Schematic diagram of PAFS in APR+.

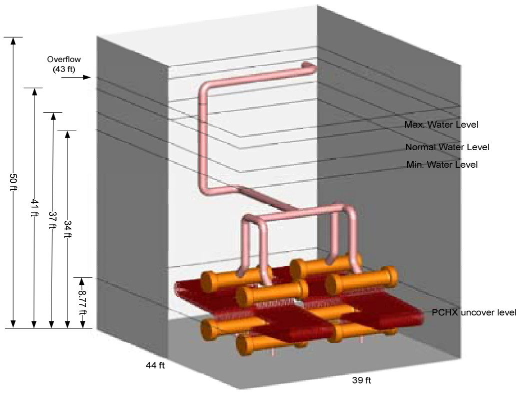

Fig. 2 Configuration of PCCT and PCHX.

For a numerical calculation based on finite volume formation, three-dimensional mesh system is generated with 16,000,000 cells which consisted of hexahedral and tetrahetral cells.

Several conservation equations are numerically solved to obtain flow and temperature fields. A volume fraction equation is solved to track the interfaces between two phases (gas - liquid; steam bubbles - cooling water) [1,2]. The momentum equation is solved to obtain velocity and pressure fields. The energy equation is solved to obtain temperature distribution. To include turbulent effects in the flow domain, the standard k-ε model is adopted, and thus the turbulent kinetic equation and turbulent kinetic energy dissipation equation are solved together. The generation of steam bubbles by boiling on the outer surfaces of the PCHX tubes is modeled using a phase change heat/mass transfer approach via UDF (user defined function).

2.1 Mass transfer

A mass transfer model concerning the process of evaporating is used via UDF. We assume that phase change is assumed to occur at a constant pressure and at a quasi thermo-equilibrium state, and the mass transfer is mainly dependent of the saturate temperature. Applied phase change process is described as

$$\begin{aligned} S &= -\gamma_l \alpha_l \rho_l \left|(T_l - T_{sat})\right| / T_{sat} \qquad T_l \geq T_{sat} \\ &= \gamma_v \alpha_v \rho_v \left|(T_{sat} - T_v)\right| / T_{sat} \qquad T_l < T_{sat} \end{aligned}$$

In this study, the interfacial temperature is assumed at the saturation temperature.

2.2 Heat transfer

The heat transfer is simply determined from the mass rate of evaporation or condensation, in addition to the conduction and convection. As long as the mass transfer is obtained, the heat transfer could be directly determined as

$$Q = -h_{LH} S$$

Transient numerical calculation is implemented in a commercial computational software with the generated mesh system and calculation conditions. Pressure-based approach is used for flow analysis. The velocity field is obtained from the momentum equation, and pressure field is extracted by solving a pressure correction equation which is obtained by manipulating continuity and momentum equations. This approach solves the governing equations for the conservation of mass and momentum, and for energy and other scalars such as turbulence. For transient simulation, the governing equations are discretized in both space and time with the second order upwind scheme and the second order implicit scheme, respectively. For the pressure-velocity coupling, the Pressure-Implicit with Splitting of Operators (PISO) pressure-velocity coupling scheme is used. The PRESTO! (PREssure STaggering Option) scheme interpolates the pressure values at the faces using momentum equation coefficients. To ensure sharp interface treatment between two phases, the explicit VOF scheme and Geo-Reconstruct scheme are used [3,4,5].

3. Results

The PCCT is initially filled up to the normal water level (37 ft). The water temperature in the PCCT is initially set to be the saturation temperature (212 ^{o}F) at atmospheric pressure. The PCCT above the normal water level (37 ft) is initially occupied by saturated steam (T_{sat} = 212 ^{o}F).The flow inside the PCCT initially set to be settle down.

Transient steam bubble generation and behavior are shown in Fig. 3. At the beginning stage, a mount of steam bubbles are generated on the outer surfaces of the PCHX tubes, and rise up forming bubble plumes. On rising, the bubble plumes are divided up into a number of small bubbles. As the rising bubbles approach the top free surface, perturbations are observed on the free surface.

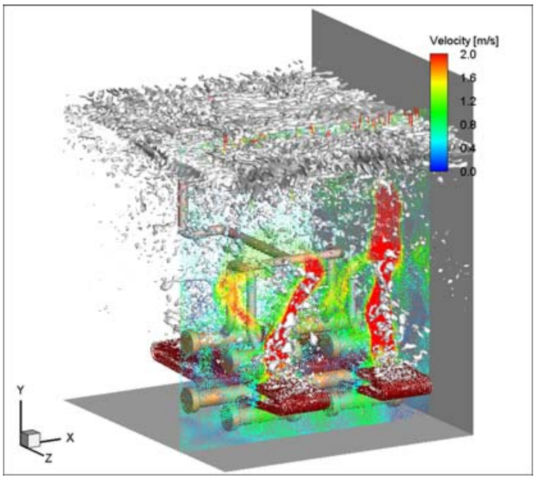

Fig. 3 Bubble behavior and velocity vectors (t=120s).

Finally (at t= 120 s), bubble generation and behavior become stable (quasi steady state). After this point, a great change in general flow patterns is not observed except the water level gets lower gradually.

Rising flows of the cooling water are induced by the rising bubbles, and mainly formed on the above sides of the PCHX bundles. As the rising water is close to the free surface, flows are forward to outer sides, and then head to downward forming circulation flows inside the PCCT.

The area of rising flows is about 66.3 m^2 which is about 42% of total cross-sectional area. The mean rising velocity is about 1.02 m/s (max.: 5.25 m/s). The total circulation flow rate becomes about 67,490.8 kg/s.

4. Conclusions

The thermal hydrodynamic phenomena in the PCCT have been successfully simulated using a computational fluid dynamics (CFD) technique. The applicability of phase change heat/mass transfer model has been proved through this study.

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