Numerical Simulation of Condensation Phase Change Flow in an Inclined Tube with ⊃-Bend

Jong Chull Jo[a*], Byung Soo Shin[a], Kyu Sik Do[a], and Yong Kap Lee[b]
[a]*Nuclear System Evaluation Dept., Korea Institute of Nuclear Safety, 62 Gwahak-ro, Yusung-gu, Daejon, Korea*
[b]*Anflux Co., 182-4 Guro-dong, Guro-gu, Seoul, Korea*
[*]*Corresponding author: jcjo@kins.re.kr*

1. Introduction

The new PWR design named APR+ incorporates a passive auxiliary feedwater system (PAFS) [1] as shown in Fig.1.

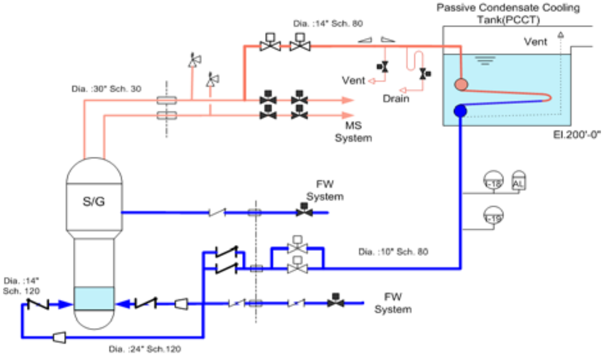

Fig. 1 Simplified analysis model of the PAFS [2]

The PAFS consists of two separate divisions. Each division is equipped with one passive condensation heat exchanger (PCHX), isolation or drain or vent valves, check valves, instrumentation and control, and pipes. It is aligned to feed condensed water to its corresponding steam generator (SG). During the PAFS normal operation, steam being produced in the SG secondary side by the residual heat moves up due to buoyancy force and then flows into the PCHX where steam is condensed on the inner surface of the tubes of which the outer surfaces are cooled by the water stored in the passive condensation cooling tank (PCCT). The condensate is passively fed into the SG economizer by gravity.

Because the thermal-hydraulic characteristics in the PCHT determine the condensation mass rate and the possibility of system instability and waterhammer, it is important to understand the condensation phase change flow in the PCHT. This paper presents a numerical simulation of the condensation phase change flow in the PCHX adopted for the APR+ PAFS.

2. Methods and Results

2.1 Analysis Model of the PCHX and PCCT

The PCHX is installed in the lower space of its corresponding PCCT. It consists of inlet and outlet headers connected together by the inclined tubes with '⊃'-shaped bend of which the slope of each straight part is 6^o (see Fig.1).

The present numerical analysis is performed for a simple model as shown in Fig.2. The model involves the PCHX tube-side flow domain, the tube solid wall, and the tank-side water pool domain. The front side of the analysis model is the symmetry plane of the tube and the back side is the symmetry plane of the two adjoining tubes. The top side is a free surface open to atmosphere at 1atm and 30 ^oC. The remaining sides of the tank are assumed to be adiabatic. The length and height of the model are 6.7 m and 8.9 m. As the pitch in a PCHX tube bundle is 0.112 m, the width is chosen to be 0.056 m. The saturated steam flowrate, temperature, and pressure at the tube inlet are 0.1475 kg/s, 290 ^oC, and 7.4 MPa, respectively. The initial temperature of water in the PCCT is 30 ^oC.

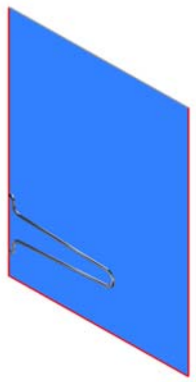

Fig.2 Analysis Model

2.2 Numerical Analysis

The single fluid multi-components flow model with the equilibrium phase change model [3] was employed for the numerical simulation of the tube-side two-phase flow accompanying condensation.

In the calculation, the transport equations of velocity, pressure, temperature and turbulence are solved for the fluid which is water-vapor mixture. The bulk motion of the fluid is numerically modeled using single velocity, pressure, temperature and turbulence fields. In the equilibrium phase change model, the phase change is taken into account by enthalpy variation. If the fluid enthalpy is not greater than the saturated liquid enthalpy, the void fraction is zero. And the enthalpy is equal to or greater than the saturated vapor enthalpy, the void fraction is 1. Otherwise, the fluid void fraction is determined according to the difference between its enthalpy and the saturated liquid enthalpy. The vapor and liquid has own density, specific heat, conductivity, viscosity and enthalpy, the influence of the multiple components is taken into account through density variation which affects conservation of mass.

For the numerical simulation of the natural convection due to boiling heat transfer outside the tube in the tank, the two fluids model and the wall boiling model [4] were used. The solution domain of fluid flow and heat transfer including the solid tube wall is calculated employing the conjugate heat transfer analysis approach. Both the tube-side and tank-side flows are simulated using the SST turbulent model.

The governing equations for the present problem can be found in ref. [3, 4]. The present numerical simulation was implemented by using the ANSYS-CFX code [5].

2.3 Discretization of the Solution Domain

The discretized model of the PAFS tube for the present numerical calculation is shown in Fig.3. The tube-side flow domain, tube wall, and the tank-side water domain are discretized into 108K hexahedral elements with 121K nodes, 42K hexahedral elements with 58K nodes, and 2000K hexahedral or tetrahedral elements with 800K nodes, respectively.

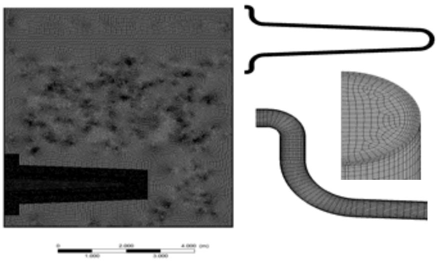

Fig.3 Discretized solution domain with enlargements

2.3 Results and Discussion

Numerical simulation of the present model is very complex and costly because it consists of the two different two-phase flow fields formed by either condensation or boiling heat transfer, which are isolated each other by a solid tube wall. To efficiently get a general insight and understanding of the condensation phase change flow inside a tube of the PCHX, a preliminary numerical calculation of the present model was performed by a quasi-steady state solution approach although it is not realistic to get a steady state solution of the boiling-induced natural convective flow.

Figures 4-7 show the typical flow situation in the tube-side domain in terms of the velocity and void fraction contours, which were obtained from the preliminary calculation. The condensation phase change process can clearly be identified from the figures.

As the follow-up study, a transient numerical simulation for the present numerical model will be performed and validation of the simulation will be made by comparing with the measured data where available.

3. Conclusions

A complex multi-phase flow and heat transfer in a PCHX tube model of the APR+ PCHX which is submerged in the PCCT was numerically simulated.

The single fluid multi-components flow model with the equilibrium phase change model was employed for the condensation phase change flow inside the tube and the two fluids model with the wall boiling model was used for the boiling-induced natural convection in the PCCT. Using the analysis model and the numerical techniques applied to the present analysis, transient numerical simulation and its validation will be proceeded as the follow-up study.

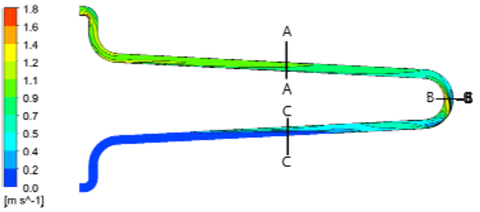

Fig.4 Velocity on the tube symmetry plane

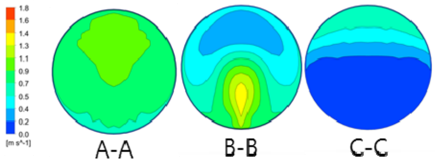

Fig.5 Velocity on the cross-sections A-A, B-B, and C-C of the tube

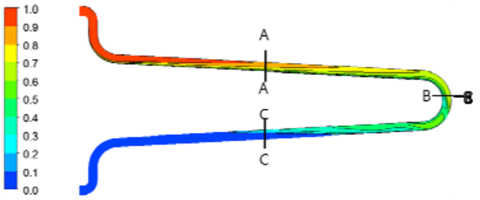

Fig.6 Void fraction on the tube symmetry plane

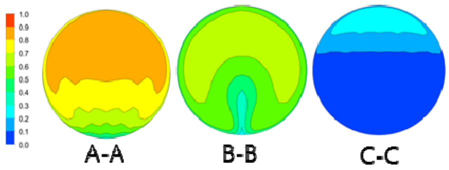

Fig.7 Void fraction on the cross-sections A-A, B-B, and C-C of the tube

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