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Development of CUPID-Heat Exchanger Model for the Simulation of the Condensation Phenomena inside the PCCS

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1. Introduction

The pressurization of reactor containment during number of design basis and severe accidents is a major safety concern in nuclear power plants. To prevent pressure buildup inside the containment. Steam released during accidents should be removed. The development of passive safety systems to guarantee the integrity of the containment in case of accidents have drawn much attention recently. Among these systems is the Passive Containment Cooling System (PCCS).

The PCCS consists of number of vertical tube banks acting as a heat exchanger. The condensation process occurs on the outer surface of the tubes. The coolant inside the tubes comes from the Passive Containment Cooling Tank (PCCT) which is located outside the containment and acts as a heat sink. The working fluid circulates between the PCCT and PCCS tubes passively, relying on buoyancy force.

Condensation inside the containment takes place in the presence of non-condensable gases such as air and hydrogen which can be generated from core damage. Many experimental [1] and analytical studies [2] showed that the presence of the non-condensable gases sharply degrades heat transfer. Thus, decreasing the rate of steam condensation. Therefore, predicating the condensation rate in the presence of the non-condensable gases is of great importance.

In the present work, the CUPID code has been utilized to develop a one tube heat exchanger model in order to simulate the condensation of the steam in the presence of air over vertical tube inside the PCCS. A component scale approach based on empirical heat transfer correlations is adapted. This approach is applicable for large reactor containment application since it allows the usage of coarse meshes. Thus, shorter computational time is needed. Wall heat transfer models are applied inside and outside of the condensing tube. Heat transferred through the tube wall is calculated solving 1D heat conduction equation. Finally. The model is validated against a small scale PCCS experiment

2. Mathematical Models

The CUPID code uses two-fluid, three-field conservation equations for multi-dimensional flows. The two fluids are liquid and vapor. And the three-field refers to gas, continues liquid, and droplets [3].

In the CUPID-HX model, the secondary side of the heat exchanger is modeled directly solving the governing equations of the CUPID code. Inside the tube, 1D mass, momentum, and energy equations are applied to the primary coolant. Heat transfer between the primary and secondary sides is calculated by adding wall heat transfer models to both sides. Pressure drop over a tube is calculated in each direction since the flow resistance over tube is anisotropic.

2.1 Wall Heat Transfer Models

Empirical heat transfer correlations are applied to the secondary and primary side of the heat exchanger tube as shown in Fig.1. Heat flux through the wall is calculated solving 1D heat conduction equation in the radial direction.

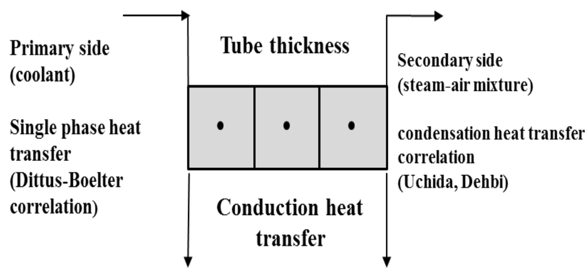

Fig. 1. Applied wall heat transfer models.

Inside the tube, single phase forced heat transfer coefficient is calculated using the Dittus-Boelter correlation:

$$Nu = 0.023 Re^{0.8} Pr^{0.4} \quad (1)$$

Where Nu is the Nusselt number, Re is the Reynolds number and Pr is the Prandtl Number.

Outside the tube, the condensation heat transfer coefficient in the presence of air, Uchida empirical correlation for steam condensation under natural convection is used [4]. In addition, a generalized correlation of the Uchida equation proposed by Dehbi [5] is implemented. Correlations of Uchida and Dehbi are as following:

$$h_U = 380\left(\frac{W_s}{1-W_s}\right)^{0.7} \quad (2)$$

$$h_D = 507\left(\frac{W_s}{1-W_s}\right)^{0.88} \quad (3)$$

where W_s is steam mass fraction.
The following assumption are considered in the calculation of the condensation heat transfer coefficient:

- The effect of the condensation film is ignored. The condensate is removed with the condensation process.
- The steam mass fraction of the wall is defined by the wall temperature.

3. Calculation Results

A small scale PCCS experiment which has been conducted at the Chung-Ang University is used to validate the developed model. In this section, description of the experiment, computational grid, and calculated results is presented.

3.1 Small Scale PCCS Experiment

Fig. 2.a shows s schematic of the small scale PCCS experiment. The inside of the closed vessel is filled with a mixture of steam and air. A condensation tube of a length of 100 cm and outer diameter of 19.05 mm is placed inside the vessel to represent the primary coolant side of a heat exchanger. Coolant enters from the bottom and leaves from the top. To maintain a constant pressure, steam is injected through a nozzle during the experiment. Condensation heat transfer coefficients were measured for different air mass fractions and pressures.

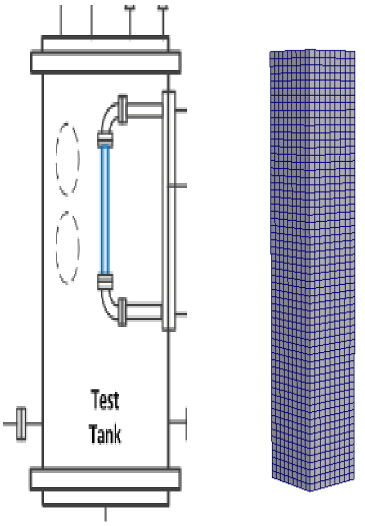

Fig. 2. (a) Small scale PCCS experiment, (b) computational grid (b).

Table 1, shows a set of condensation tests that were used to validate the proposed model.

Table I: Condensation tests

	Air mass fraction	Pressure (Bar)	Coolant flow Rate (kg/s)
Test1	0.2900	2	0.036
Test2	0.4000	2	0.036
Test3	0.4466	2	0.036
Test4	0.3460	3	0.036
Test5	0.5260	3	0.036

3.2 Computational Grid

For grid sensitivity purpose, four meshes were generated for the CUPID-HX model. All cells were modeled as structured hexahedral volumes. In each mesh, the number of the vertical cells are kept the same while changing the number of the cells in the axial direction. Comparison between the four meshes is shown later in this section.
Fig. 2.b shows the reference computational grid of 4860 cells. Steam inlet was added to the side of the vessel to simulate steam nozzle. Adiabatic boundary conditions were assigned to the walls of the vessel. The tube was modeled as a porous media inside the vessel.

3.3 Results

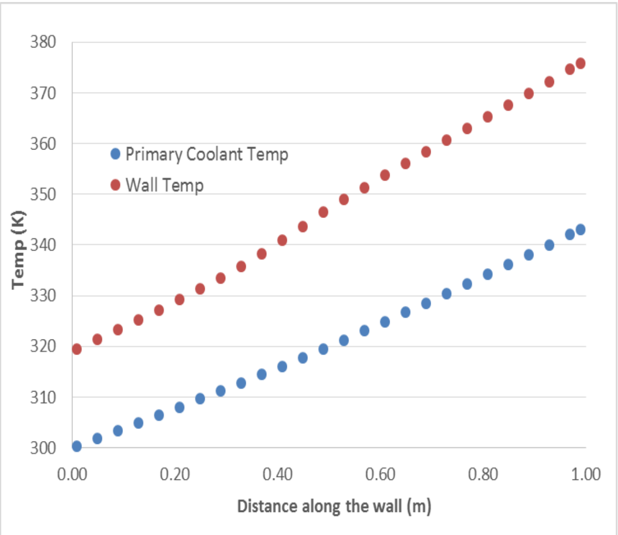

Fig. 3. Primary coolant and wall temperatures along the cooling tube.

Primary coolant and wall temperature profiles are shown in Fig.3. Cooling water is injected at the bottom with initial temperature of 300 K. Water is heated as it moves upward and cooldown the steam and non-condensable gas mixture inside the vessel.
Fig.4. and Fig.5. Show a comparison between the calculated heat fluxes and experimental data at 2 and 3 bars respectively. The calculated and experimental HTC values in these figures are the averaged values of the HTC along the wall.

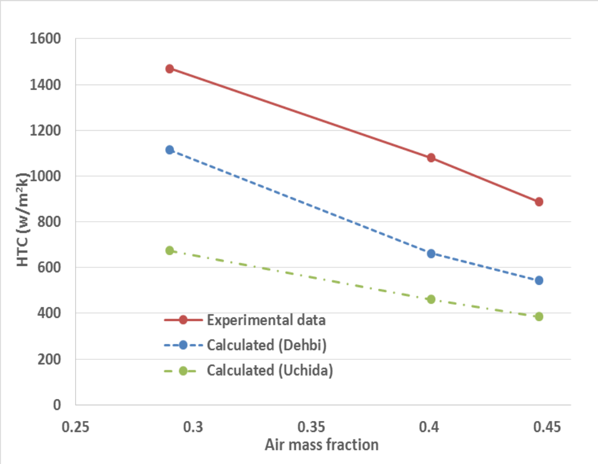

Fig.4. Heat transfer coefficient for different air mass fraction at 2 bar.

Fig.4. compares the calculated and the experimental results for the test cases 1-3. Test cases 4, 5 are compared in Fig.5.

As can be seen from the figures, the condensation heat transfer coefficient decreases as the air mass fraction increases. This is because the non-condensable gas is accumulated near the liquid film creating a layer that impedes steam diffusivity.

Results from Dehbi correlation showed better agreement against the experimental results than the ones obtained using Uchida correlation. Because, Uchida correlation was developed based on data from an experiment that has different geometry and parameters. Dehbi correlation is a generalized one and independent on test geometry. It can be noted that Dehbi correlation ability to predict the heat transfer coefficient of the condensation decreases as pressure and mass fraction increase.

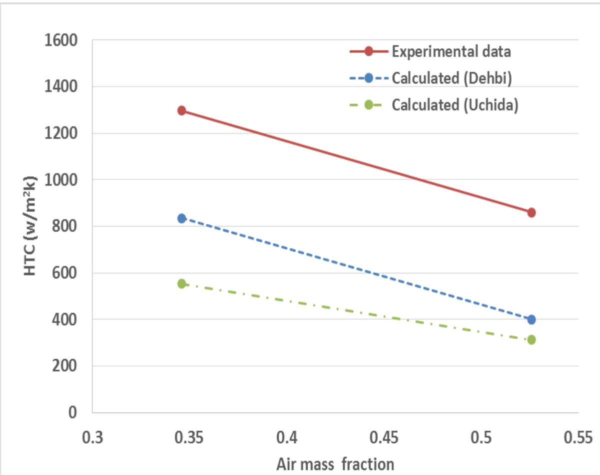

Fig. 5. Heat transfer coefficient for different air mass fraction at 3 bar.

Sensitivity study of the four generated meshes for test1 is shown in Fig.6. The calculation is done using Dehbi correlation. As the cooling tube was modeled using porous medium approach, the smallest cell size is limited by the outside diameter of the tube. That is corresponding to 6000 mesh. Grid sensitivity tests using bigger mesh sizes were conducted and confirmed that even if the number of cells is halved. The difference in the HTC values is still relatively small. 4860 mesh was chosen to be a reference case.

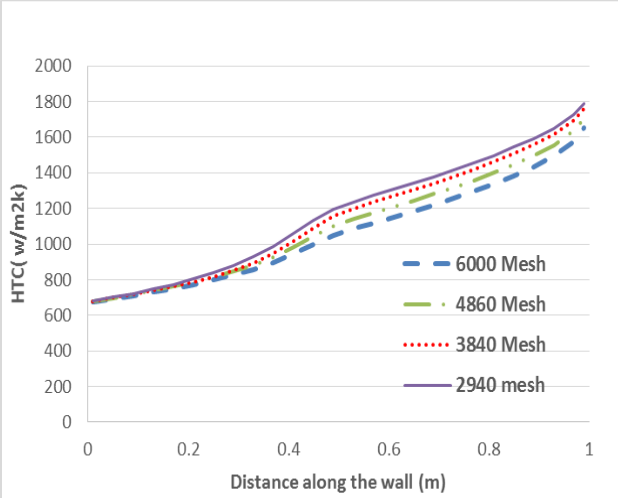

Fig. 6. Sensitivity study of the computational grid.

4. Conclusion

In the current study, the CUPID-HX model has been developed for the simulation of the steam condensation in the presence of air inside the PCCS over vertical tube. Wall heat transfer models were applied for the primary and the secondary sides of the heat exchanger tube. Two empirical correlations were used to calculate the condensation heat transfer coefficient. The proposed model was validated against small scale PCCS experiment. Calculated results of the heat transfer coefficients as a function of the air mass fraction obtained by Dehbi correlation showed better agreement with the experimental data. Uchida correlation under predicted the heat transfer coefficients significantly. Mainly, this is due to different experiment geometry and conditions upon which the Uchida correlation was derived. Grid sensitivity study is presented and confirmed the independency of the model on mesh cell number.

In the future, this model will be extended to simulate bundles of vertical tubes and new empirical correlations will be added. Additionally, validation against various test conditions will be performed.

Acknowledgment

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REFERENCES

[1] A. Dehbi , M.W Golay, M.S. Kazimi, Condensation experiments in steam–air and steam–air–helium mixtures under turbulent natural convection, National Heat Transfer Conf., AIChE, Minneapolis,p.19-28,1991.
[2] J.W. Rose, Approximate equations for forced convection condensation in the presence of a noncondensing gas on a flat plate and horizontal tube, Int. J. Heat Mass Transfer 23, p.539–546,1980.
[3] CUPID Code Manual.Vol.1: Mathematical Models and Solution Methods, KAERI, 2018.
[4] H. Uchida, A. Oyama, and Y. Togo, Evaluation of post incident cooling systems of light-water power reactors, Proceeding of International Conference on Peaceful Uses of Atomic Energy, Vol. 13, p. 93, 1965.
[5] A. Dehbi, A generalized correlation for steam condensation rates in the presence of air under turbulent free convection, Int. Heat Mass Transfer 86, p.1-15, 2015.