Capability of MARS-KS on Predicting Wall Condensation in the Presence of Non-Condensable Gases

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1. Introduction

Wall condensation occurs when vapor contacts a surface cooler than its saturation temperature. There are two types wall condensation which are “filmwise” and “dropwise”. In filmwise condensation, the entire surface is covered by condensate where it flows continuously whereas the surface is covered by stagnant drops (up to a certain size) in dropwise condensation. Primary work was made by Nüsselt (1916) [1] in wall condensation for pure vapor. It’s known that boiling and condensation are the most efficient type of heat transfer however, it has demonstrated by many experiments since 1960s that even a small amount of non-condensables can greatly reduce the condensation heat transfer rate [2]. Effects of non-condensable gases play a very important role during in some of Design Basis Accidents (DBAs) such as Loss of Coolant Accident (LOCA), and design of heat exchangers such as Passive Containment Cooling System (PCCS) where condensation takes place in high amount of non-condensables on containment walls and/or surface of components. Therefore, it is decided to investigate the capability of MARS-KS [3] on wall condensation by simulating the four tests of COPAIN [4] experimental facility.

2. Test Facility and Modelling

In this section, COPAIN test facility is briefly introduced with the selected tests. The facility is modelled in 1D and 3D which are described in modelling section with the condensation model of MARS-KS.

2.1 COPAIN Test Facility

COPAIN test facility, as shown in Figure 1 has been operated by CEA in France, is a rectangular channel with a cross-sectional area and length of 0.3 m^2 (0.6 m x 0.5 m) and 3 m, respectively. The condensing plate is 0.6 m in width and 2 m in length whose thickness is 25 mm and made of stainless steel. The system is a close loop where the steam and air is injected from the top and let the steam condensate on the plate. Then condensate and gases are collected separately and sent to boiler and gas injection line, respectively. As a heat sink, a secondary circuit provided to keep the condensing plate cooled at a constant temperature. The selected tests that were simulated are listed in Table 1.

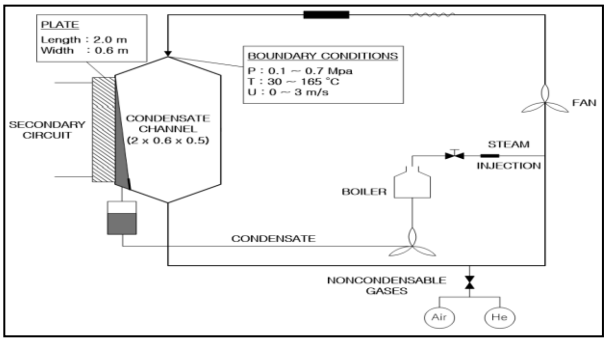

Fig.1. COPAIN Test Facility

Table I: Selected COPAIN Test

Test No	Convective Heat Transfer	Inlet Air Velocity (m/s)	Pressure (bar)	Air Inlet Temperature (K)	Wall Temperature (K)	Mass Fraction X_{NC}
P0441	Forced	3	1.02	353.23	307.40	0.767
P0443	Free	1	1.02	352.33	300.06	0.772
P0444	Natural	0.5	1.02	351.53	299.70	0.773
P0344	Natural	0.3	1.21	344.03	322.00	0.864

2.2 MARS-KS Models

MARS-KS 1.4 (Multi-Dimensional Analysis of Reactor Safety), which has been developed by KAERI by consolidating the thermal hydraulic system code RELAP5/MOD3.2 with integration of multi-dimensional subchannel analysis code COBRA-TF), was used to simulate the selected COPAIN tests in both 1D and 3D.

2.2.1 Modelling in 1D

COPAIN facility was firstly modelled in 1D, as depicted in Figure 2, with a pipe component divided into 12 sub-volumes (Component #120) where adiabatic walls are allowed at the top and bottom leaving the center as a condensing section. Time dependent volumes (Component #100 & #140) are connected to the condensate channel with a time dependent junction (Component #110) at the inlet and a single junction (Component #130) at the outlet. To allow the heat transfer, 10 heat structures were modelled, as the right hand sides of the heat structures were connected to the pipe, the left hand sides connected to a fix temperature boundary to represent the secondary circuit using table function in MARS-KS. All simulations were performed up to 2000.0 seconds.

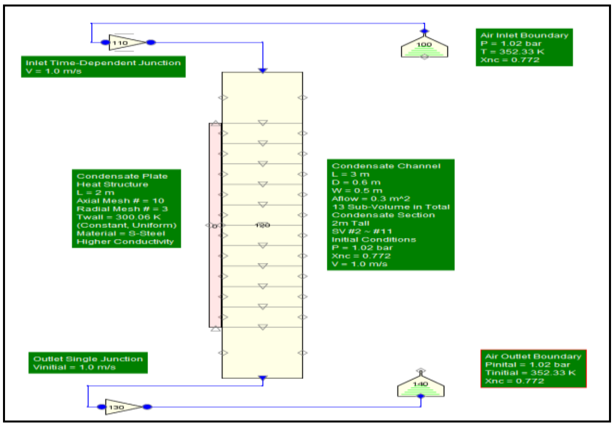

Fig.2. 1D Nodalization

2.2.2 Modelling in 3D

Same tests are also simulated in 3D as shown in Figure 3 to investigate the multidimensional effects. Modelling idea is similar to that of 1D however; the condensation channel is divided into 3x6x12 meshes in x, y, z direction, respectively. It is aimed to resolve the velocity profile therefore near wall cells are smaller in size then the far ones.

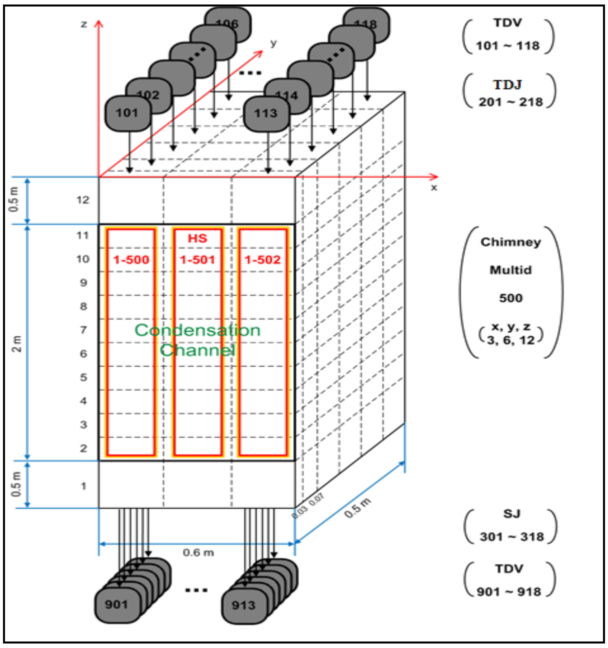

Fig.3. 3D Nodalization

2.2.3 Condensation Model in MARS-KS

In MARS-KS, condensation model is to use the maximum of Nusselt (laminar) [1] and Shah (turbulent) [5] correlation with the Colburn-Hougen [6] iterative diffusion calculation to solve for the interface temperature between steam and the condensate when noncondensable gases are present. Colburn-Hougen model indicates that liquid and gas heat fluxes are equal at the interface. So, if the interface temperature is known, then the total heat flux could easily be calculated. However, the interface temperature is not equal to the saturation temperature of the vapor when the non-condensables are present. Thus, initial guess of interfacial temperature based on the wall temperature leads the code the predict interface temperature and condensate heat transfer coefficient with an iteration process. After the equation is converged, the heat flux is calculated.

3. Results

Four of selected COPAIN tests were simulated using both one-dimensional and multi-dimensional approaches in MARS-KS. The comparison of heat flux results are depicted in Figure 5. Firstly, it is observed that multi-dimensional effects played a really important role predicting the heat flux. As it can be seen from the results, heat flux predicted almost constant along the condensate plate using one-dimensional method whereas multidimensional approach gave relatively better results. However, none of the approaches were able to capture the sharp power gradient at the entrance region (i.e. where the flow develops). It should also be noted that heat flux of both approaches have gotten worse as the flow type changes from forced to natural convection.

Considering the heat flux results, it is decided to check the flow fields. Two representative tests are depicted in Figure 4 for the flow types of forced (P0441) and natural (P0444) convection with inlet velocities 3 m/s and 0.5 m/s, respectively. In case of forced convection, maximum gas velocity was observed across the wall in contrast in case of natural convection, maximum gas velocity was observed near the wall.

4. Conclusions

Comparison of heat flux results indicated that MARS-KS is capable of predicting average heat flux in forced convection using 3D model. However, it is observed that none of the approaches are suitable to capture sharp power drop at the entrance region. Thus, the applicability of the correlations (Nusselt and Shah) should be checked when simulating geometries like COPAIN. It is known that Shah model is developed based on a tube geometry and Colburn-Hougen model is based on heat and mass transfer analogies where the flow is assumed to be fully developed. As already known, the velocity vectors should be resolved near the wall to get a good estimation of heat flux. However, MARS-KS is firstly developed as lumped parameter code, thus it has a limited capability of resolving the velocity vectors. Thus, although the proper correlations/models would be used, the code may not be able to estimate the heat flux accurately due to its nature.

It is observed that MARS-KS produced velocity vectors reasonably well. In the case of forced convection, the maximum gas exit velocity (~3.2 m/s) was observed on the wall across from the condensing wall. The highest gas exit velocity (~0.7 m/s) was observed near the condensing wall in the case of natural convection due to condensation. Mass of air is heavier near the wall than bulk, thus this result in higher density and faster gas velocity near the wall. It should also be noted that even though wall friction effects are included in the input model, MARS-KS could not simulate the velocity decrement near the wall across the condensing plate. Sensitivity tests were performed by decreasing the mesh interval size and on roughness, however the reason could not be investigated fully yet.

As future work, it is decided to perform more sensitivity tests on the velocity field, mesh numbering and hydraulic diameter.

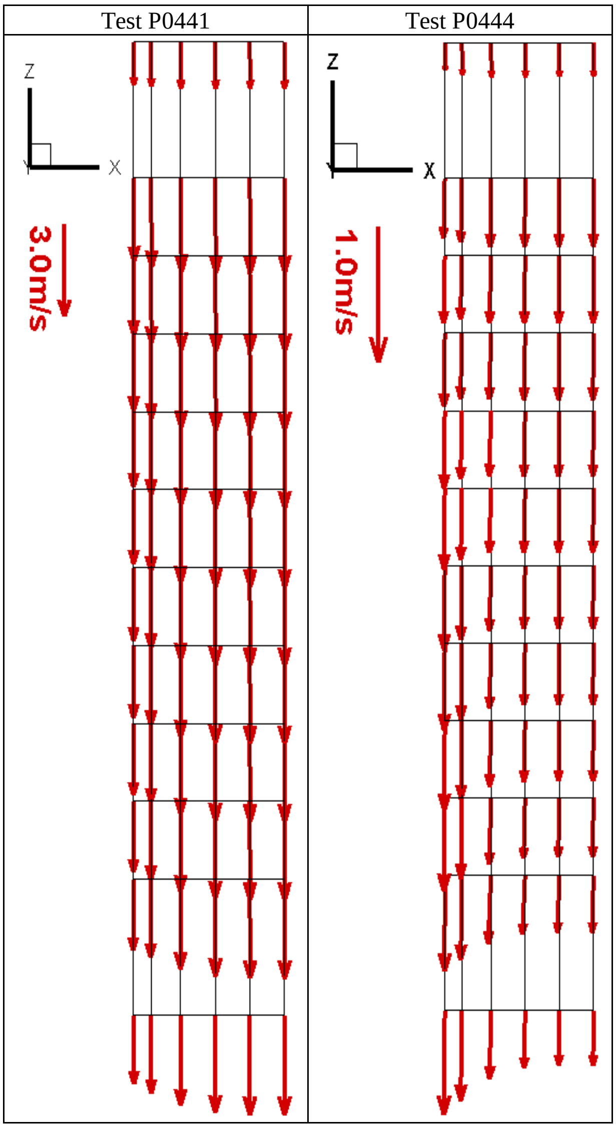

Fig.4. Gas Velocity Distribution along the Channel

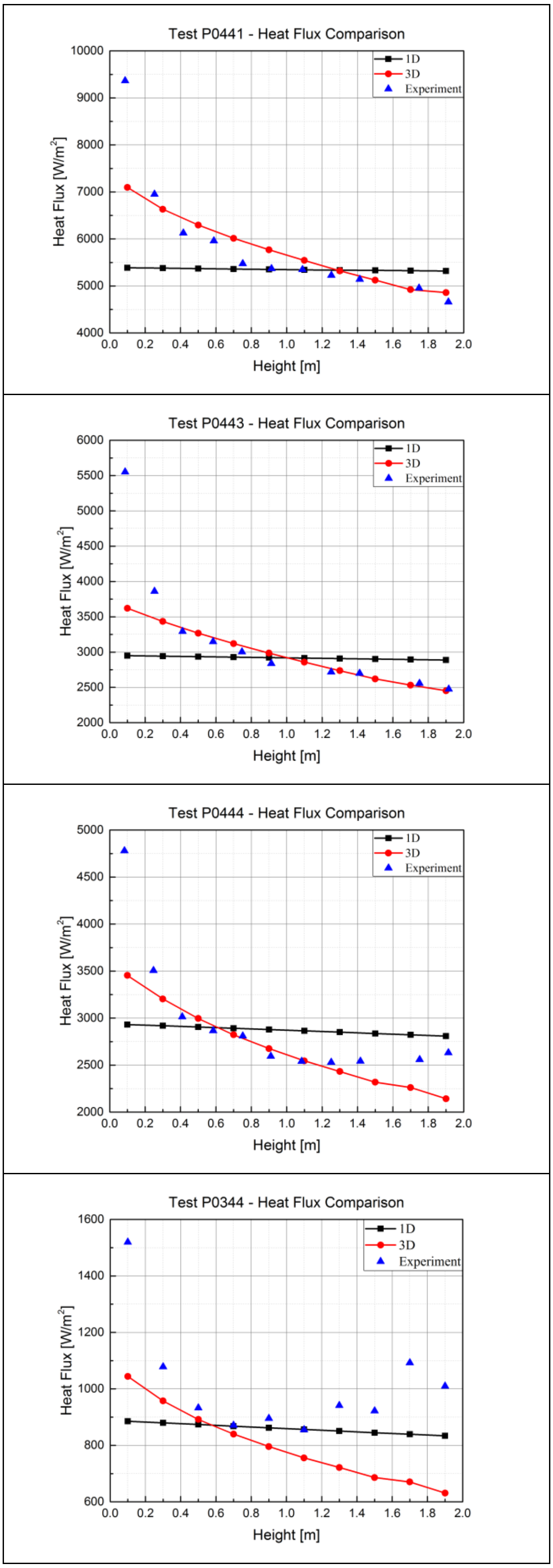

Fig.5. Heat Flux Results

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