Analysis of a double-pipe heat exchanger performance using heat structure coupling of MARS and CUPID

M. Amidu[a], H. K. Cho[b], H. Kim[a*]
[a]*Department of Nuclear Engineering, Kyung Hee University, Yongin, Korea*
[a]*Department of Nuclear Engineering, Seoul National University, Seoul, Korea*
[*]*Corresponding author: hdkims@khu.ac.kr*

1. Introduction

The influence of wall orientation angle on the heat transfer rate has been established in the work of Kang (2013) in which the local heat transfer coefficient has been shown to decrease as azimuthal increases from the bottom to the top of the tube circumference. In order to predict these phenomena in single-tube heat exchanger accurately, a sophisticated two-phase thermal hydraulic analysis is required and the need for this prediction motivated the simulation of the heat exchanger through a coupling between a multi-dimensional code and a one-dimensional system analysis code.

Thermal hydraulic phenomena in the inner tube of the double-pipe heat exchanger are expected to be reproducible by one-dimensional system analysis codes (MARS) if a proper condensation heat transfer coefficient is applied. Jeon et al (2013) and Cho et al (2013) conducted comprehensive reviews of the predictive capability of the condensation heat transfer models for the steam-water stratified flow.

On the contrary, in the outer tube, a multi-dimensional analysis tool is required to incorporate the influence of azimuthal angle on the heat transfer rate from the inner tube outer wall to the outer tube fluid. Therefore, a coupled calculation between one-dimensional system analysis code and a multi-dimensional computational fluid dynamics code is an attainable way to predict this effect with a reliable accuracy.

CUPID is a three-dimensional computational multi-phase fluid dynamics code developed by KAERI (Korea Atomic Energy Research Institute). According to Jeong et al (2010), the objective of the development is to support a resolution for the thermal hydraulic issues regarding the transient multi-dimensional two-phase phenomena which can arise in an advanced light water reactor. It uses two-fluid model for the governing equations, which uses two sets of Navier-Stokes' equations for two phases. It can be used as either a typical CFD code or a component code (porous CFD code) depending on the length scale of the phenomena that need to be resolved.

On the other hand, MARS is a best estimate thermal-hydraulic system code and it was developed at KAERI by consolidating and restructuring the RELAP5/MOD3.2 code and COBRA-TF code (Cho et al., 2014). The MARS code has the capability to analyze best-estimated thermal hydraulic system.

In this study, the coupled CUPID-MARS code was used for the simulation of a double-pipe heat exchanger. This paper presents the description of the heat exchanger, the coupling method, and the simulation results using the coupled code.

2. Methods and Results

In this study, explicit heat structure coupling of CUPID and MARS was carried out for the purpose of analyzing a double-pipe heat exchanger. The heat exchanger consists of two separated systems. The primary system is the steam supply system in the inner tube while the secondary system is the coolant flowing in the outer tube. The interface between the two systems is defined by the inner tube which prevent flow interaction but allows heat transfer.

The two-phase phenomena inside the inner tube including condensation and the phase stratification were calculated by MARS and those in the outer tube including boiling phenomenon were modeled with CUPID as shown in Fig 1.

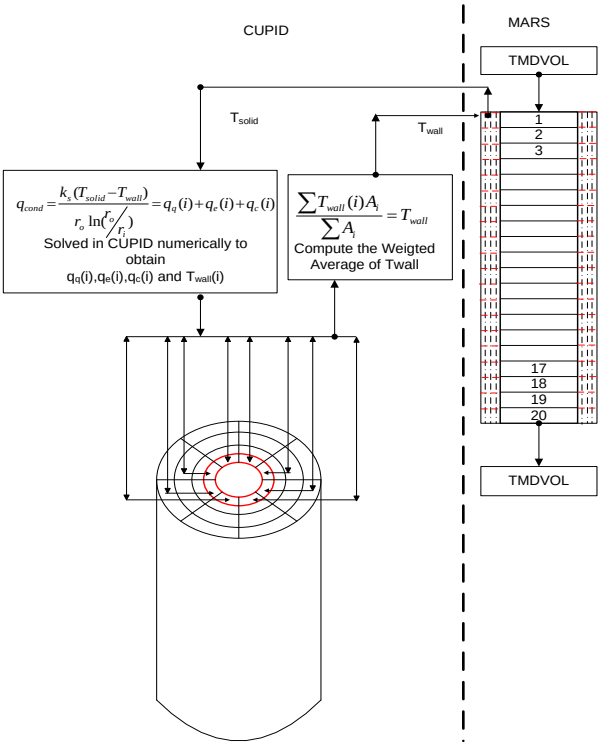


Fig. 1. CUPID-MARS Coupling Approach

The coupling between the two codes was achieved by sharing the surface temperature of the inner tube and its second outmost solid temperature at every time step by using the interactive control function of the MARS as described in the work of Cho et al. (2014). The use of interactive control function allows exchange of designated pointer variables between MARS and CUPID when CUPID calls the Dynamic Link Library (DLL) of the MARS.

In the first instance, MARS solves hydrodynamic equations and the conduction equations with given boundary conditions including the inner tube outer wall temperatures. Afterwards, the second outmost solid temperatures (T_{solid}) is transferred from MARS to CUPID as shown in Fig 2. With this solid temperature, CUPID uses flow variables inside the outer tube (fluid temperature (T_{fluid}), liquid velocity etc) calculated by itself to solve the energy balance equations in order to obtain the outer wall temperature (T_{wall}). The heat balance equation is the combination of the conduction equation with the wall heat partitioning model proposed by Kurul and Podowski (1991) as stated in equation (1) to equation (5).

$$q''_{cond} = \frac{k_s(T_{solid} - T_{wall})}{r_{out} \times \ln\left(\frac{r_{out}}{r_{in}}\right)} = q''_{in} \quad (1)$$

$$q''_{in} = \left[q''_c + q''_q + q''_e\right] \times f(\theta) \quad (2)$$

$$q''_c = h_c A_{1f}\left(T_{wall} - T_{fluid}\right) \quad (3)$$

$$q''_q = \left(\frac{2}{\sqrt{\pi}}\sqrt{t_w k_l \rho_l C_{pl} f}\right) A_{2f}\left(T_{wall} - T_{fluid}\right) \quad (4)$$

$$q''_e = N'' f \left(\frac{\pi}{6} D^3_{b,depart}\right) \rho_g h_{fg} \quad (5)$$

Where A_{1f}: single-phase heat transfer area ratio, A_{2f}: two-phase heat transfer area ratio, t_w: bubble waiting time, f: bubble departure frequency, N'': active nucleation site density, $D_{b.depart}$: bubble departure diameter and $f(\theta)$ is the correction factor for the influence of the orientation angle of the interfacing cell

The azimuthal angle (θ) of all the interfacing cells were computed using the dot product of the user-defined gravity vector and surface normal vectors in the CUPID as shown in Fig 2.

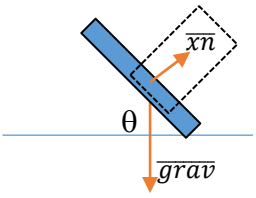


Fig. 2. Determination of Inclination Angle

The inclination angle is calculated using equation (6) where $\overline{xn}$ is the unit surface normal vector and $\overline{grav}$ is the gravity vector.

$$\cos(\theta) = \frac{\overline{xn} \cdot \overline{grav}}{|\overline{xn}||\overline{grav}|} \quad (6)$$

The weighted average of the wall temperatures for the boundary cells at each coupling interface is transferred to MARS thereby replacing the temperature boundary condition of the conduction equation in MARS in this step. MARS solves the conduction equation using the received wall temperature with the convective boundary condition imposed on the inner wall of the tube. As a result of this calculation, the radial temperature distribution across the tube thickness is obtained. Lastly, the second outmost temperature of the heat structure was delivered again to CUPID for new time step calculation. This procedure was repeated for all the interface cells of CUPID.

The validation of the coupled code was done by simulation of a vertically oriented double pipe in which the time step difference and heat balance between the two codes were checked at steady state as shown in Fig 3.

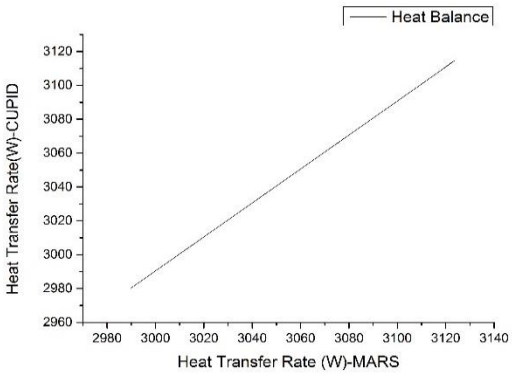
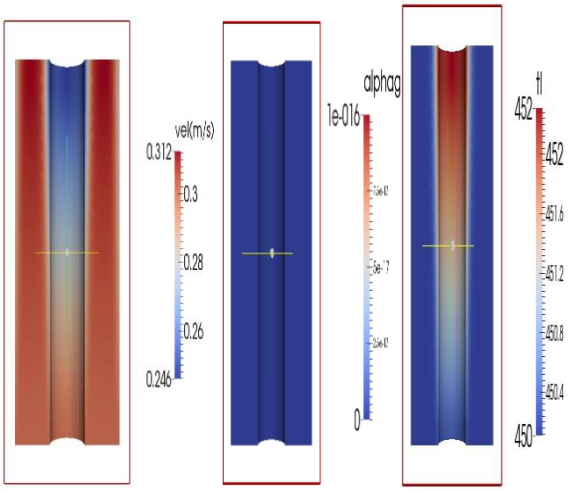


Fig.3. Heat Balance between CUPID and MARS

With this vertical orientation of the heat exchanger, all the interface cells are at right angle to the gravity vector, so the influence of orientation angle was not considered for this scenario.

The single phase simulation results are shown in Fig 4. Fluid enters the tube with a uniform velocity of 0.3m/s but as the fluid makes contact with the surface, viscous effects become important and boundary layer develops with increasing tube length. Towards the end of the tube, the velocity at the boundary drops to 0.24ms/s as shown in Fig 4(a).



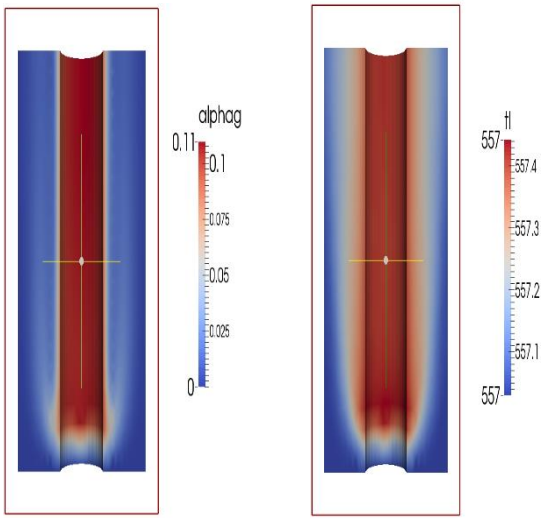
a. b. c.

Fig 4. Single Phase Simulation ((a) velocity in the outer tube (b) Void Fraction in the outer tube (c) Liquid Temperature (K))

The initial condition of the coolant is subcooled with initial temperature of 450 K at 6.89 MPa which is far below the saturated temperature of 557 K at the same pressure. Therefore, single phase heat transfer is expected and this is ascertained by the zero void fraction at the end of the simulation as shown in Fig 4(b). The fluid temperature rises from the initial value of 450 K to 452 K at the outlet of the tube and expectedly the inlet is maintained at 450 K as shown in Fig 4(c)

On the other hand, the void fraction in the inner tube that was modelled with MARS decreases from 0.94031 at the inlet to 0.92438 at the outlet which depicts that condensation takes place in the inner tube.

In addition, the two-phase simulation was also carried out by raising the initial liquid temperature to the saturation temperature of 557 K and the results obtained are shown in Fig 5.



a. b.

Fig.5. Two Phase Simulation ((a) Void Fraction (b) Liquid Temperature (K))

The void fraction substantially increased as shown in Fig 4(a) while the liquid temperature hovered around the saturated temperature because most of the heat transfer were used in vapor generation.

3. Conclusions

The coupling of CUPID with MARS has made the multi-scale thermal-hydraulic analysis feasible and robust. It was found that the overall two-phase behaviors in the inner tube (Condensation) and in the outer tube (Boiling) in the heat exchanger were well reproduced with the coupled code.

Studying of the influence of wall orientation angle and comparison of various parameters between the experimental results and simulation will be performed in the future for a qualitative analysis and verification of the coupled code.

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