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Computational study of wall condensation phenomena in the presence of non-condensable gases containing a light gas by using CUPID-MARS coupled code

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1. Introduction

In the presence of non-condensable gas, as a heat sink of the vapors emitted from the primary side of the nuclear power system, condensation is a typical phenomenon in a postulated loss-of-coolant accident. Besides, the wall condensation of steam in the containment building is a phenomenon that directly affects the pressurization and the flow distribution in the containment building [1]. Thus, the condensation of steam affects the distribution of non-condensable gases including hydrogen that can be released to containment in postulated accidents. In the past decade, various experiments have been conducted on the condensation of vapors and the distribution of non-condensable gases, and analysis has been conducted using CFD codes and system analysis codes [2, 3]. However, in general, CFD codes need a high computational cost and lumped-parameter (LP) codes have inherent limitations to simulate multi-dimensional flow phenomena. Therefore, the CFD-LP code coupling method has been studied gradually to simultaneously use the CFD codes with strengths in multi-dimensional analysis and LP codes with numerical efficiency [4]. In particular, various conceptual analyses were carried out with heat structure coupling between MARS-KS and CFD codes such as ANSYS/FLUENT, STAR-CCM+, and OpenFoam using socket communication at Seoul National Universtiy .

In this study, CUPID-MARS code coupling was established by applying a socket communication to CUPID and MARS. the modified version of CUPID for the analysis of the condensation of the ternary gas mixture in our previous work [5], was used to the code coupling. Verification analysis of coupled code was performed to analyze the wall condensation phenomena in the presence of non-condensable gas mixture containing a light gas.

2. Computational analysis

2.1 Code coupling method

In this study, a socket communication-based interface program was used to the heat structure coupling of MARS-KS and CUPID codes. This interface program was generalized for heat structure coupling with CFD scale codes [6]. This method was chosen because it facilitates the data transfer between codes on different operation systems, for example, the coupling between one code on a Windows system and the other on a Linux machine, such a high performance computer system.

As illustrated in Fig. 1, pre-determined exchange variables are transferred through the socket server. At this time, each code can be connected while performing calculations in different computing devices and OSs. In this study, the region where condensation occurred were analyzed by using the CUPID code, and the region where single-phase and conduction heat transfer were analyzed by using MARS-KS. The exchange variables are transferred at every time step in both codes. As shown in Fig. 2, pre-determined exchange variables were wall temperatures and wall heat fluxes which were calculated by MARS-KS and CUPID respectively. Also, to maintain the consistency in time marching, the time step of CUPID, which is relatively smaller than that of MARS-KS, was used as the time step of MARS-KS. Since the grid of CUPID code is finer than that of MARS-KS, mapping of exchange variables was carried out. The surface averaged heat flux calculated from CUPID is transferred to MARS-KS, and the linear fitted wall temperature calculated from MARS-KS is transferred to CUPID.

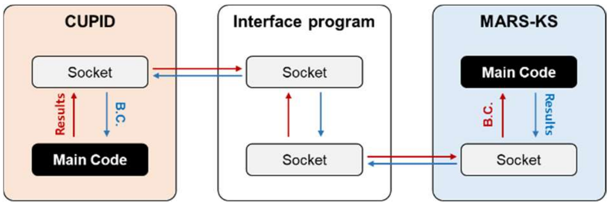

Fig. 1. MARS-CUPID code coupling with socket communication scheme

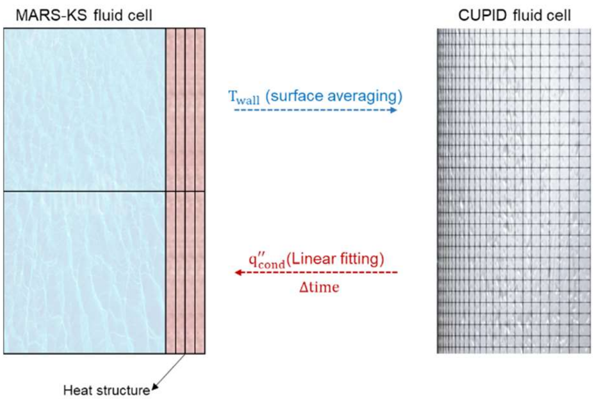

Fig. 2. MARS-CUPID heat structure coupling diagram

2.2 Wall condensation simulation

To verify and validate the coupled code, the CONAN experiment, which is a separate effect test for condensation heat transfer, was analyzed [7]. As described in Fig. 3(a), CONAN test facility consists of the primary side where the wall condensation occurs, and the secondary side for cooling the condenser wall. MARS-KS was used to simulate the secondary side and aluminum plate, CUPID to calculate condensation heat flux on the primary side. The nodalization of MARS-KS and computational meshes in the CUPID is presented in Fig. 3(b) and (c). MARS-KS nodalization consists of a pipe that flows cooling water and a heat structure that simulates an aluminum plate. For using the CUPID RBLA condensation model which was improved before, 70,000 meshes were generated and wall y^+ was kept below 1 [8]. Standard $k-\varepsilon$ turbulence model was used and turbulence production due to buoyancy was considered. Calculated test conditions are presented in Table. 1. As mentioned before, the surface averaged condensation heat flux and linear fitted wall temperature were calculated and transferred to each code. To evaluate the analysis results of the coupled codes, the results were compared with the experimental results and the calculation results of the STAR-CCM+-MARS coupled code. The CONAN test simulation with the another coupled code had been performed in our previous work [9].

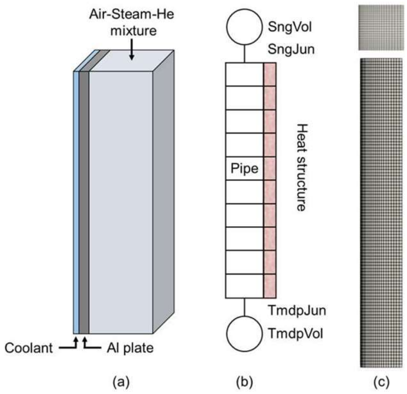

Fig. 3. Computational domain, nodalization of MARS-KS and computational meshes of CUPID for CONAN test simulation

Table I: Computational Conditions of CONAN Test Simulation

P20-T50-V30-H08	$\dot{m}_{sec}\,[kg/s]$	$T_{in,sec}$ [°C]		$T_{out,sec}$ [°C]
	0.9536	50.2		53.6
	$V_{out,pri}[m/s]$	$T_{in,pri}$ [°C]	$Y_{in,air}$ [−]	$Y_{in,He}[-]$
	3.11	92.0	0.402	0.005
P20-T50-V30-H65	$\dot{m}_{sec}\,[kg/s]$	$T_{in,sec}$ [°C]		$T_{out,sec}$ [°C]
	1.0832	49.7		52.7
	$V_{out,pri}[m/s]$	$T_{in,pri}$ [°C]	$Y_{in,air}$ [−]	$Y_{in,He}[-]$
	3.06	89.1	0.223	0.056
P05-T40-V06-H62	$\dot{m}_{sec}\,[kg/s]$	$T_{in,sec}$ [°C]		$T_{out,sec}$ [°C]
	0.7232	39.9		40.9
	$V_{out,pri}[m/s]$	$T_{in,pri}$ [°C]	$Y_{in,air}$ [−]	$Y_{in,He}[-]$
	~0.6	76.9	0.429	0.093
P05-T40-V06-H90	$\dot{m}_{sec}\,[kg/s]$	$T_{in,sec}$ [°C]		$T_{out,sec}$ [°C]
	0.6901	40.5		41.7
	$V_{out,pri}[m/s]$	$T_{in,pri}$ [°C]	$Y_{in,air}$ [−]	$Y_{in,He}[-]$
	~0.6	71.1	0.190	0.219

2.3 Simulation results

As shown in Figure 4, in the case of forced convective condensation, where the fluid velocity at the inlet is high, the CUPID-MARS coupled code analysis results slightly overestimate the local condensation heat flux. It is supposed that turbulent mixing near the wall is largely calculated. In general, when the standard k-ε turbulence model is used with fine mesh, near wall turbulent characteristics are overestimated [10]. Nevertheless, as shown in Fig. 4 and 5, except for the P05-T40-V06-H62 case, the CUPID-MARS coupled code shows good agreement with the experimental results and STAR-MARS analysis results regardless of the flow condition. Also, as shown in Figure 6, except for the P05-T40-V06-H62 case, the total heat transfer by the secondary loop was predicted within a 20% error. This was discussed in previous research because the standard k-ε turbulence model is not suitable for the analysis of the P05-T40-V06-H62 case. Shortly, except for the specific case, the CUPID-MARS analysis results corresponded to the experimental and STAR-MARS analysis results.

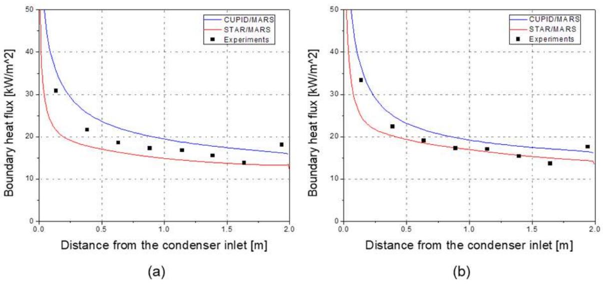

Fig. 4. Local condensation heat flux: forced convective condensation
(a: P20-T50-V30-H08, b: P20-T50-V30-H65)

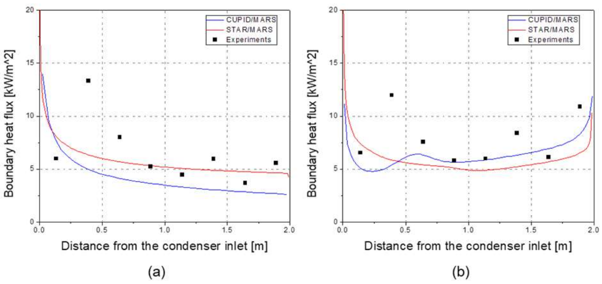

Fig. 5. Local condensation heat flux: natural convective condensation
(a: P05-T40-V06-H62, b: P05-T40-V06-H90)

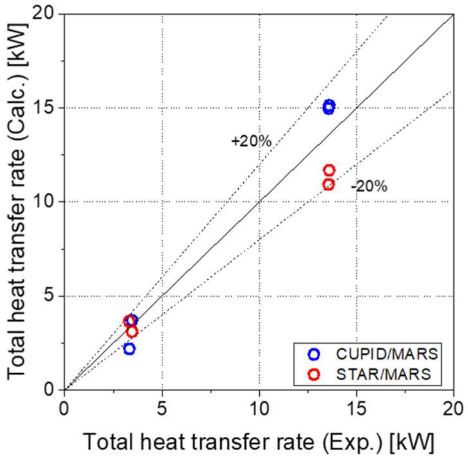

Fig. 6. Comparison of total heat transfer rate

3. Conclusion

In this study, code coupling was performed using an interface program, and condensation heat transfer analysis was conducted with coupled code. For the code coupling, MARS-KS and CUPID were used. To verify the CUPID-MARS coupled code for the condensation heat transfer phenomena in the presence of a non-condensable gas including a light gas, an analysis was performed against the CONAN experimental tests. Except for a specific case where the turbulence model showed the limitation, the local condensation heat flux and total condensation heat transfer showed reasonable results. Therefore, it was concluded that the wall condensation phenomena of the ternary gas mixture (steam-air-helium) can be simulated using the CUPID-MARS coupled cide realized with the socket communication. In the future, it is expected that the coupled code can be used to analyze large containment experimental systems or passive containment cooling systems.

Acknowledgement

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REFERENCES

[1] Bucci, M., Ambrosini, W., & Forgione, N. (2013). Experimental and Computational Analysis of Steam Condensation in the Presence of Air and Helium. Nuclear Technology, 181(1), 115–132.

[2] Paladino, D., Auban, O., Huggenberger, M., & Dreier, J. (2011). A PANDA integral test on the effect of light gas on a passive containment cooling system (PCCS). Nuclear Engineering and Design, 241(11), 4551–4561.

[3] Allelein, H. J., Gupta, S., Poss, G., Reinecke, E. A., & Funke, F. (2017) German Experimental Activities for Advanced Modelling and Validation Relating to Containment Thermal Hydraulics and Source Term. IAEA-CN-251.

[4] Szabó, T., Kretzschmar, F., & Schulenberg, T. (2014). Obtaining a more realistic hydrogen distribution in the containment by coupling MELCOR with GASFLOW. Nuclear Engineering and Design, 269, 330-339.

[5] Lee, C. W., & Cho, H. K. (2019) Computational analysis of wall condensation in the presence of non-condensable gas mixture containing a light gas with CUPID, Transactions of the Korean Nuclear Society Spring Meeting 2019.

[6] Yoo, J. S., Choi, D. K., Cho. C. R., Cho, H. K., Coupling of MARS-KS and STAR-CCM+ and Preliminary Calculation for Multi-scale Thermal-hydraulic Analysis, Korean Society for Fluid Machinery, 2019.

[7] M. Bucci, Experimental and computational analysis of condensation phenomena for the thermal-hydraulic analysis of LWRs containments, Ph. D. thesis, University of Pisa, 2009.

[8] Lee, C. W., & Cho, H. K. (2019). Modification of CUPID Code for Wall Condensation Phenomena in the Presence of Non-Condensable Gas Mixture Containing a Light Gas. Transactions of American Nuclear Society, 121(1), 1725-1728.

[9] Lee, C. W., Yoo, J. S., & Cho, H. K. (2019) Heat structure coupling of MARS-KS and STAR-CCM+ for wall condensation in the presence of non-condensable gases containing light gas, Transactions of the Korean Nuclear Society Autumn Meeting 2019.

[10] CD adapco, CD-adapco USER GUIDE STAR-CCM+ Version 13.02, CD-adapco, 2013