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Experimental study and Validation of MARS code for CCFL in Passive Emergency Core Cooling System (PECCS) of Public Acceptable Simple SMR (PASS) system

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1. Introduction

Because of high safety and marketability of small modular reactors (SMR), many countries are actively developing SMRs. KAIST also has developed a public acceptable simple SMR (PASS) system that applies the safety-related design characteristics of high temperature gas-cooled reactors (HTGR) to a water-cooled reactor [1]. There is a new innovative safety system for decay heat removal, a passive emergency core cooling system (PECCS), in PASS system. The PASS-PECCS is comprised of a cavity pipe with a cavity valve, a cavity pipe with a rupture disc, a reactor cavity and a steel containment (Fig. 1). The cavity pipes pass through the upper part of the reactor vessel. When the PECCS is working, the steam generated in the reactor vessel releases through a cavity pipe and the water condensed on the inner wall of the steel containment is supplied into the reactor vessel through the cavity pipe. Then, the countercurrent flow limitation (CCFL) can occur in the cavity pipe. However, there was no research for CCFL investigating a high water head effect (several meters) of an upper tank and a high condensation effect due to the high water head of the upper tank in horizontal or inclined tube like the operating conditions of the PASS-PECCS.

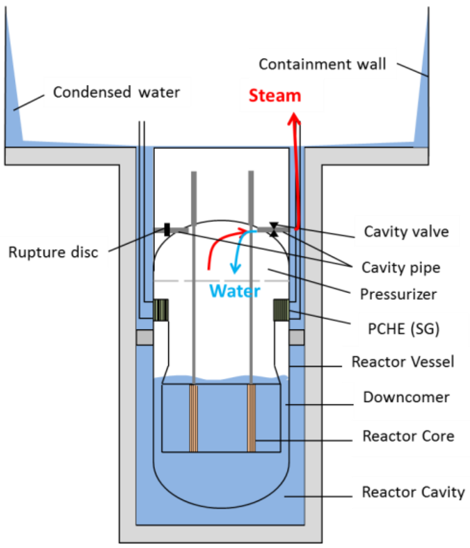

Fig. 1. Schematic diagram of PASS-PECCS

In this study, down-scaled experiments were conducted to understand the CCFL phenomena appearing in the PASS-PECCS. We focused on the high water head effect of upper tank in an air/water condition, in order to simplify the phenomena. For a full-scale simulation of the PASS-PECCS using the MARS code, we proposed a new methodology simulating the CCFL phenomena without conventional CCFL correlations and validated the MARS code based on the new methodology with the results of the down-scaled experiments.

2. Experimental study

2.1 Experimental apparatus

Fig. 2 shows the down-scaled experimental apparatus of PASS-PECCS. The diameter of the cavity pipe was scaled down to 2.5cm (around 1/4 of real scale) and the length to diameter ratio of the cavity pipe was preserved to 3. The 45° inclined tube was installed as the cavity pipe. The entrance and exit geometry of the cavity pipe are sharp. The terms entrance and exit will be used to denote the water entrance and exit of the cavity pipe.

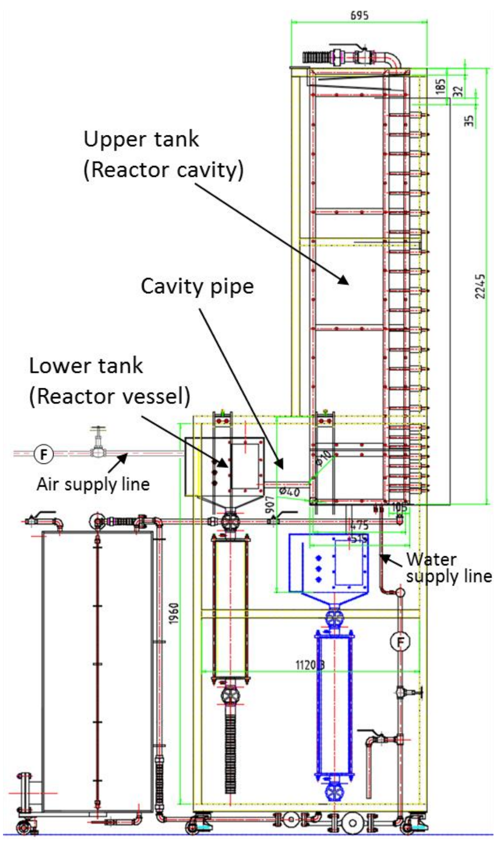

Fig. 2. Experimental apparatus of PASS-PECCS

2.2 Results and Discussion

The CCFL experiments were conducted in both a no water head condition and a 2m water head condition. In the both CCFL experiments using the 45° inclined tube (D=2.5cm, L/D=3), flooding occurred at the exit of the cavity pipe. We found that the zero liquid penetration limit of the 2m water head case is higher than the no water head case and unlike the no water head case there is no hysteresis effect in the 2m water head case. Fig. 3 shows the effect of 2m water head in upper tank. As the air supplying rate becomes higher, the difference of CCFL lines between 2m water head case and no water head case becomes larger. At the zero penetration condition, the volume flow rate of 2m water head case is 12.2% higher than one of no water head case. The enhancement of the water penetration in 2m water head case is thought to be due to recirculation of water in the upper tank. In the no water head case, water level in the upper tank is the same as the entrance position of the cavity pipe, so at the entrance region in the upper tank, water flows horizontally toward the entrance of the cavity pipe. In the 2m water head case, however, we observed strong recirculation of water in the upper tank. The recirculation makes multi-dimensional flow dynamics of water near the entrance region. The multi-dimensional flow dynamics reduces horizontal flow velocity of water at the entrance region, then water can penetrate into the cavity pipe more smoothly than no water head case.

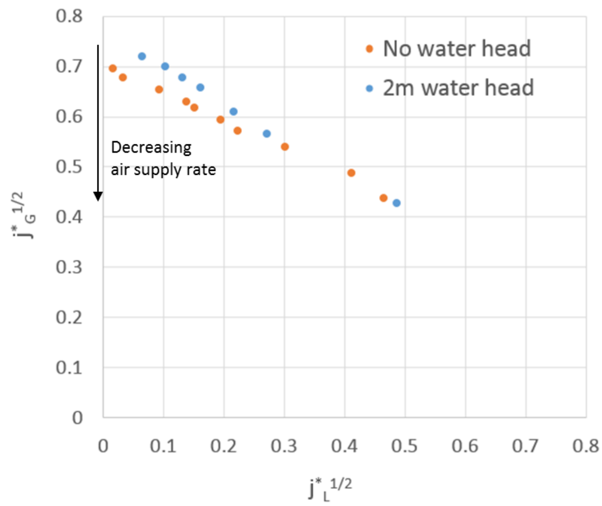

Fig. 3. Effect of water head in upper tank

3. MARS code study

3.1 New approach for CCFL simulation

The conventional approach for CCFL simulation using system codes such as MARS is using the CCFL correlation presented in terms of Wallis parameter or Kutateladze number. However, we proposed a new approach which does not utilize the CCFL correlation to get more realistic simulation results. Because the new approach does not use the CCFL model option of MARS code, we needed to establish the best nodal methodology for CCFL analysis which can give physically reasonable results. The key points of the nodal methodology are as follows: (1) The upper tank should be nodalized with at least two-dimensional volume to model the multi-dimensional effect such as recirculation of two-phase flow in the upper tank. (2) The first volume size of the upper tank connected with cavity pipe and the first volume size of the cavity pipe connected with the upper tank should be reduced enough to predict the liquid fraction reasonably at the water entrance region of the cavity pipe and remove the nodal size dependency for the form loss factor at the junction between the cavity pipe and the upper tank.

3.2 Results and Discussion

Fig. 4 shows the nodalization diagram for the down-scaled experimental apparatus of PASS-PECCS based on the new approach.

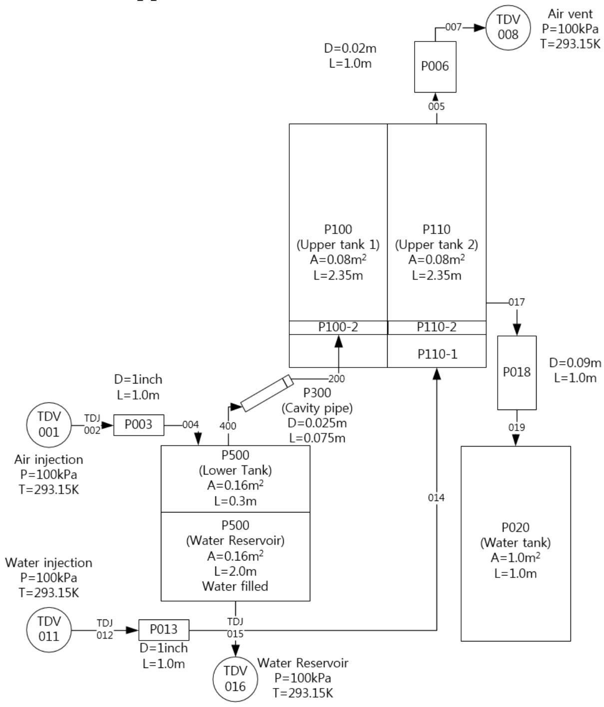

Fig. 4. Nodalization diagram for the experimental apparatus of PASS-PECCS

Fig. 5 shows the CCFL diagram of MARS code simulation and experimental results for the no water head case. MARS code results were validated by the experimental results. MARS code results were consistent with the real phenomena. As Fig. 5, we could observe hysteresis in the MARS code simulation as well as the experimental results and similar trend in the flow regime transition. In addition, flooding occurred at the same position in the both results as the water exit position of the cavity pipe.

In the MARS code analysis, the most important input parameters are form loss factors at the water entrance and exit junction of the cavity pipe, junction 200 and 400 respectively in Fig. 4. The form loss factors of the MARS simulation for the no water head case are as follows: (1) The forward and reverse form loss coefficient at the single junction 200 are 2.0. (2) The forward and reverse form loss coefficient at the single junction 400 are 17.5 and 2.5. The CCFL diagram is highly sensitive to the forward form loss coefficient of the single junction 400. The value of the forward form factor at the single junction 400 is much higher than the single phase form loss factor. This value is thought to be due to strong interactions between falling liquid film and incoming gas near the exit. Jeong and NO (1996) also explained exit flooding in sharp exit geometry condition by the same mechanism [2].

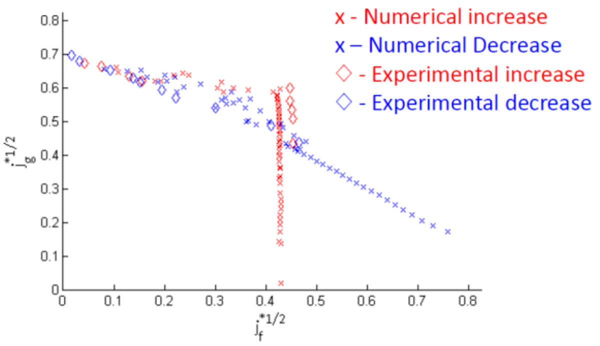

Fig. 5 CCFL diagram of MARS code simulation and experimental results for no water head case

4. Conclusions

The PECCS is the key safety system of the PASS system for removing decay heat passively and safely. CCFL is the most related phenomena appearing in PASS-PECCS. In order to understand the CCFL phenomena appearing in the PASS-PECCS, down-scaled experiments were conducted in air/water condition. We found the 2m water head in upper tank enhances water penetration compared with the no water head case. From the MARS code analysis, we proposed a new methodology simulating the CCFL phenomena without CCFL correlations and validated the nodal methodology with the experimental results. A full-scale simulation of the PASS-PECCS with MARS code will be conducted based on the new methodology developed in this study.

ACKNOWLEDGMENTS

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