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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ABSTRACT

KAIST 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. There is a new innovative safety system for decay heat removal, a passive emergency core cooling system (PECCS), in PASS. Countercurrent flow limitation (CCFL) is the most influential 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 conditions. From experimental study, we found that water head in an upper tank enhances water penetration into a lower tank compared with no water head case and there is an optimal water head condition. For a full-scale simulation of the PASS system using the MARS code, we proposed a new methodology simulating the CCFL phenomena without CCFL correlations and validated the nodal methodology with the results of the down-scaled experiments.

KEYWORDS
Countercurrent flow limitation, passive emergency core cooling system, public acceptable simple SMR, MARS code

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 cavity valve is opened by DC or AC power. If additionally the cavity valve is not opened by any accidents, the rupture disc installed in another cavity pipe bursts over the specific pressure by pressure buildup in the reactor vessel. Then the steam generated in the reactor vessel releases through a cavity pipe and the steam is condensed on the inner wall of the steel containment. The condensed water passively accumulates in the reactor cavity by gravity and the accumulated water is supplied into the reactor vessel through the cavity pipe. Therefore the cooling water can be naturally recirculated until total decay heat is removed. Because of the rupture disc, PASS-PECCS can be fully passive safety system.

However, steam and water flow in opposite direction through the cavity pipe. If the steam flow rate is high, the water flow is restricted by the steam and partially or totally cannot flow in the opposite direction. In this way, the countercurrent flow limitation (CCFL) or flooding can occur in the cavity pipe.

There are two main factors affecting CCFL characteristics, as follows: (1) water head in the reactor cavity (2) steam condensation by the cavity water. In this study, however, we did not consider steam condensation effects and focused on water head effects of the upper tank in an air/water condition, in order to simplify the phenomena. There were several previous researches investigating water head effects of an upper tank in CCFL phenomena. Sudo and Ohnuki (1984) investigated water head effects of an upper tank with in 0.05, 0.15, and 0.30m water head conditions [2] and Ghiaasiaan et al. (1996) considered 0.10 and 0.20m water heads [3]. In both studies, flow paths were vertical. There were no significant head effects in both studies. Ohnuki (1986) tested 0.02 and 0.10m water head effects in horizontal tube connected to inclined riser, but there were also no significant effects [4]. Navarro (2005) investigated the effect of the water head (0, 0.04, 0.085, and 0.13m) in the hot leg geometry and there were slight reductions of water penetration [5]. Like this, previous researches showed no significant effects or little reductions of water penetration. However, we were able to produce opposite experimental results in this study based on PASS-PECCS conditions.

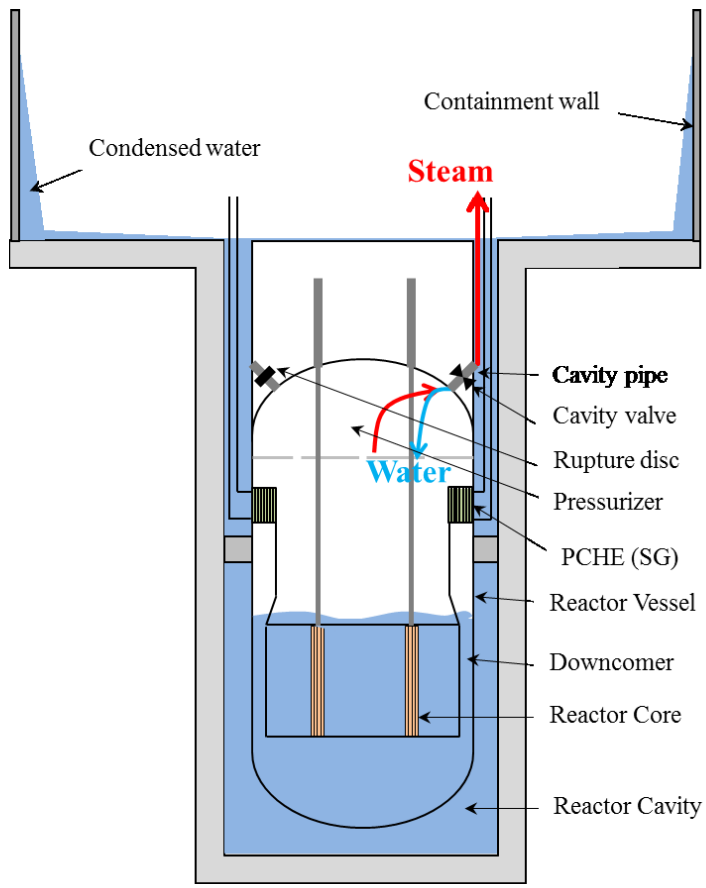

Figure 1. Schematic diagram of PASS-PECCS

In order to understand the CCFL phenomena appearing in the PASS-PECCS, we conducted down-scaled experiments in air/water condition. 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. In PASS-PECCS, the minimum diameter of cavity pipes is determined by the rupture disc because there is a manufacturing limitation on the size of a rupture disc. The maximum size of a rupture disc depends on operating pressure. Based on a normal operating condition of PASS system, the manufacturable maximum size of the rupture disc is expected to be around 15cm. In this experiment, the diameter of the cavity pipe was scaled down to 2.5cm (around 1/6 of real scale). The length to diameter ratio of the cavity pipe was preserved to 3. The inclined angle of the cavity pipe can be between 0° and 90°. In this study, the 45° inclined tube was installed as a reference condition. 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. In all experiments, water supply rate into the upper tank was maintained at around 3L/min.

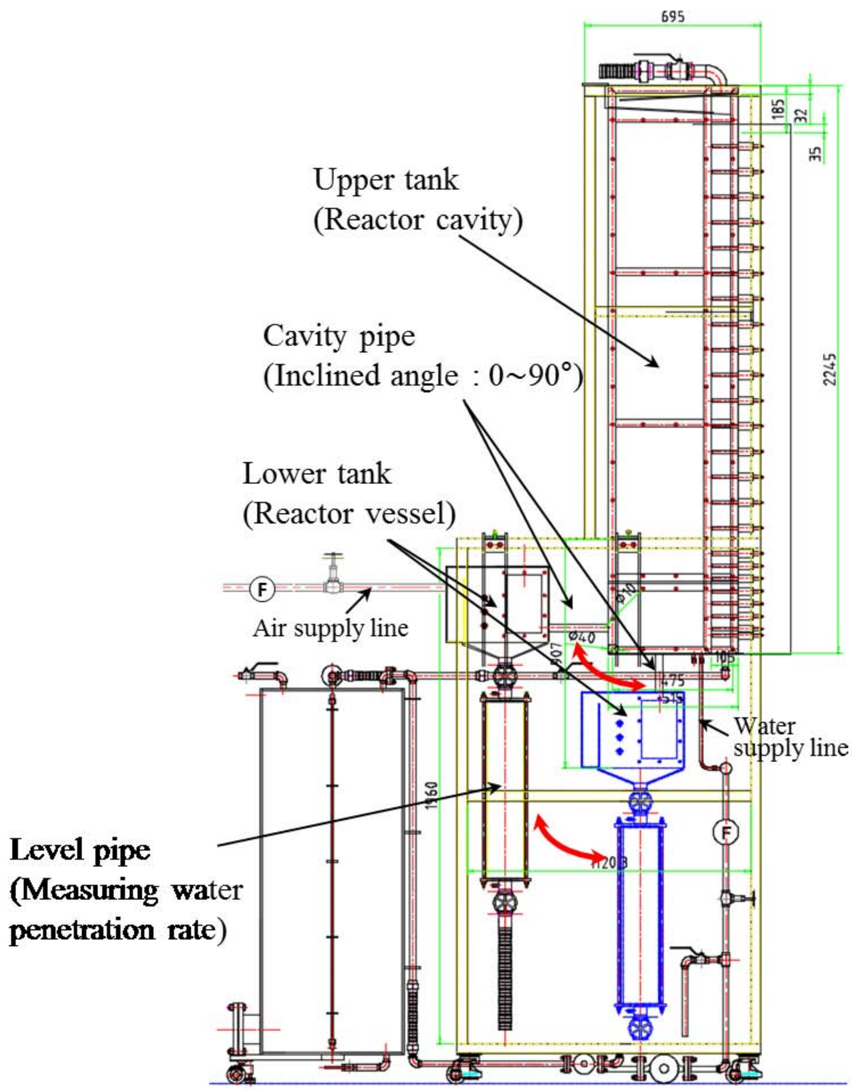

Figure 2. Experimental apparatus of PASS-PECCS (unit: mm).

2.2. Results and Discussion

The CCFL experiments were conducted in a no water head condition and various water head conditions. Fig. 3 shows the experimental result of the no water head case. The result shows hysteresis effect like previous CCFL researches. However, if there is water head in the upper tank, hysteresis effect disappears like Fig. 4. Fig. 4 shows the experimental result of 0.25m water head case.

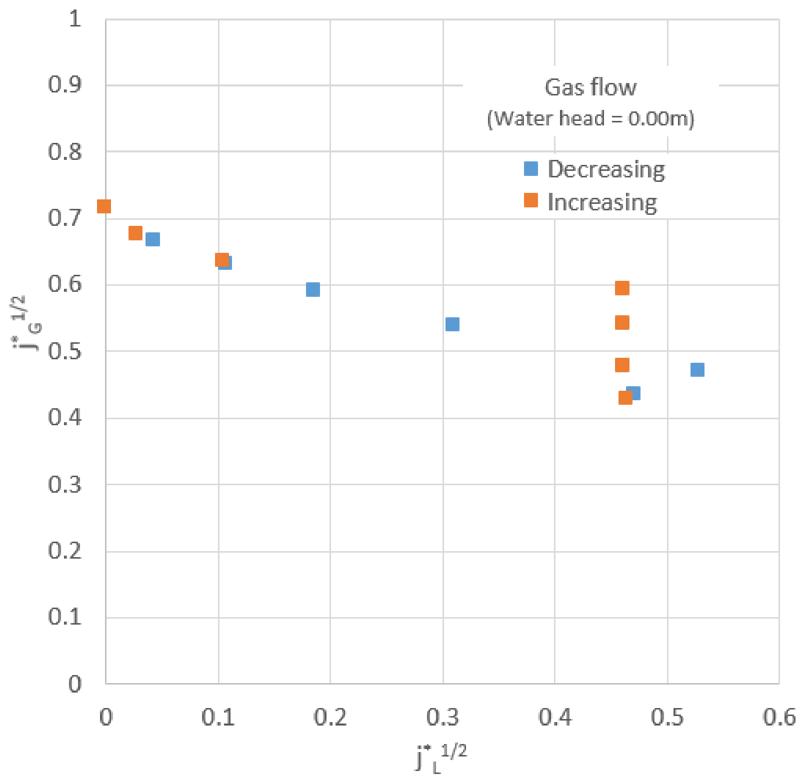

Figure 3. Experimental results of the no water head in the upper tank.

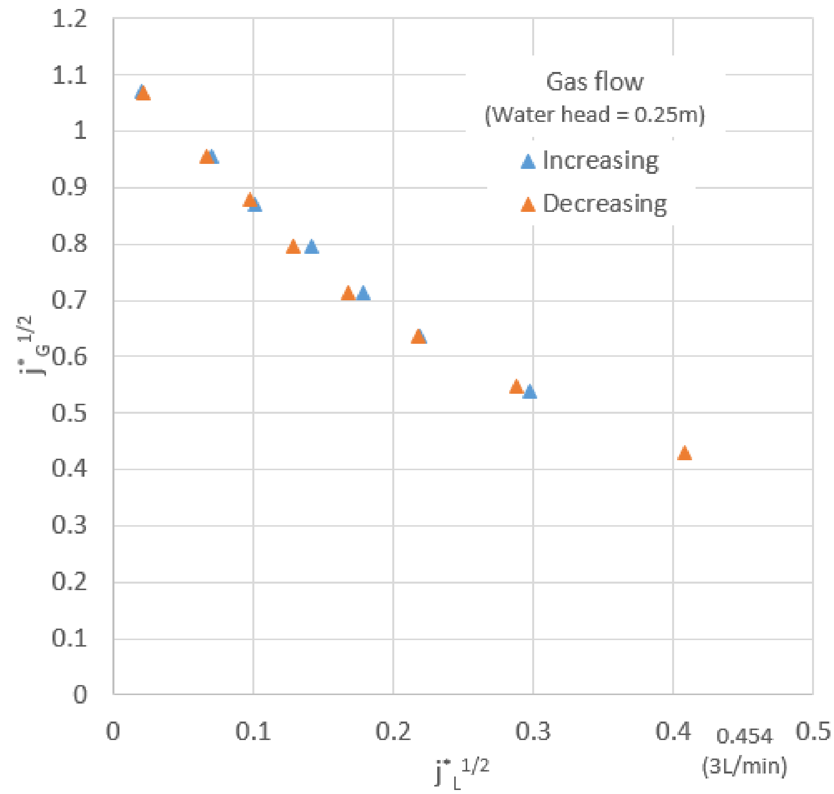

Figure 4. Experimental results of the 0.25m water head in the upper tank.

Because in the PASS-PECCS operating condition a gas (steam) flow rate decreases continuously as decay power decreases, we are concerned about the condition decreasing gas flow rates. Since there is no hysteresis in water head condition, from now on, we will not classify the trend of gas flow rates in water head cases. Fig. 5 shows various water head effects of the upper tank. As shown in Fig. 5, 0.25m water head case has the highest water penetration rate in $0.55 < j_G^{*1/2} < 0.85$ and 0.35m water head case has the highest water penetration rate in $j_G^{*1/2} > 0.85$. The differences between the no water head case and various water head cases become larger at high gas flow rates. As $j_G^{*1/2} < 0.55$, the no water head case has higher water penetration rate than the water head cases. Fig. 6 shows the phenomena in the cavity pipe in the 0.25m water head case at $j_G^{*1/2} = 0.80$. As Fig. 6, in the water head cases at $j_G^{*1/2} > 0.55$, water is continuously oscillating in the cavity pipe and in this manner water penetrates discontinuously into the lower tank. In the water head cases, the first mode sloshing was observed and it became stronger as a gas flow rate increases and water head of the upper tank approaches 0.25m or 0.35m.From this study we found that water penetration rate does not always increase with the water level in the upper tank and there is an optimal water head condition. In further works, we will investigate a mechanism enhancing water penetration by water head of the upper tank and find the optimal condition. Then, we will be able to explain the results of this study which were opposite to the results of the previous researches.

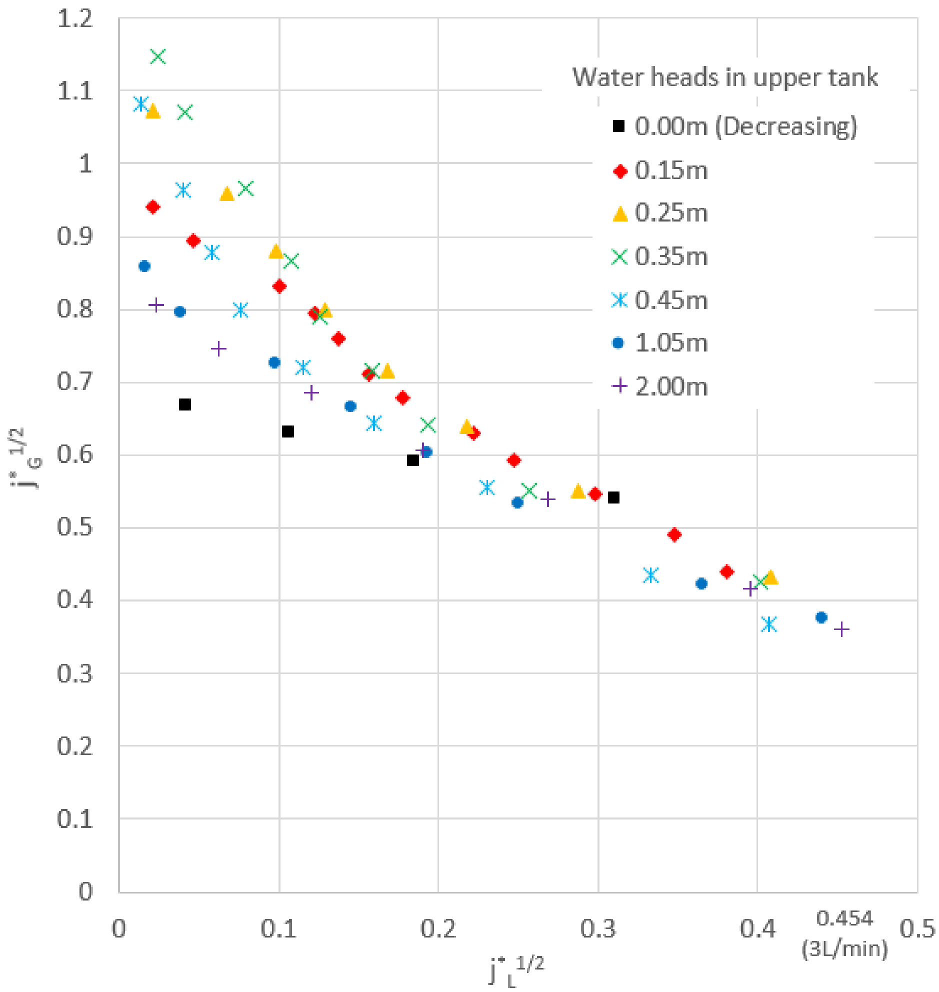

Figure 5. Effects of water head in upper tank on CCFL characteristics

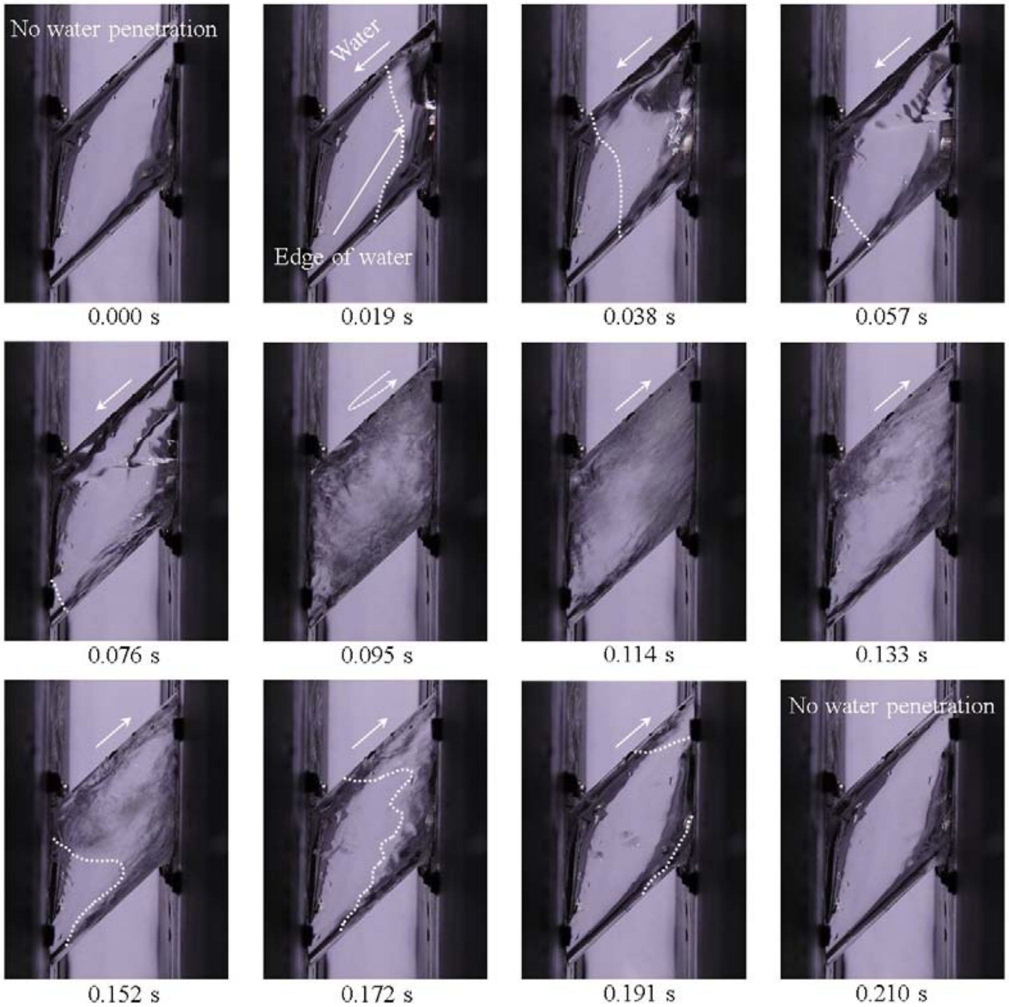

Figure 6. Phenomena in the cavity pipe in the 0.25m water head case ($j_G^{*1/2} = 0.80$).

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 a CCFL correlation presented in terms of Wallis parameter or Kutateladze number. However, CCFL correlations should be developed by experiments. Therefore, in the conventional approach, it is hard to get accurate CCFL simulation results without the CCFL correlations based on the experiments which have the exactly same conditions as the simulation conditions. Therefore, we proposed a new approach which does not utilize CCFL correlations but is based on physically reasonable nodal methodology and form loss coefficients at CCFL junctions. In the new approach, if we can get form loss factors at CCFL junctions without experiments, we don't need to perform experiments. Currently, we expect that form loss factors may be obtained by analytical approaches and CFD analysis. In the new approach, we also need 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. 7 shows the nodalization diagram for the down-scaled experimental apparatus of PASS-PECCS based on the new approach.

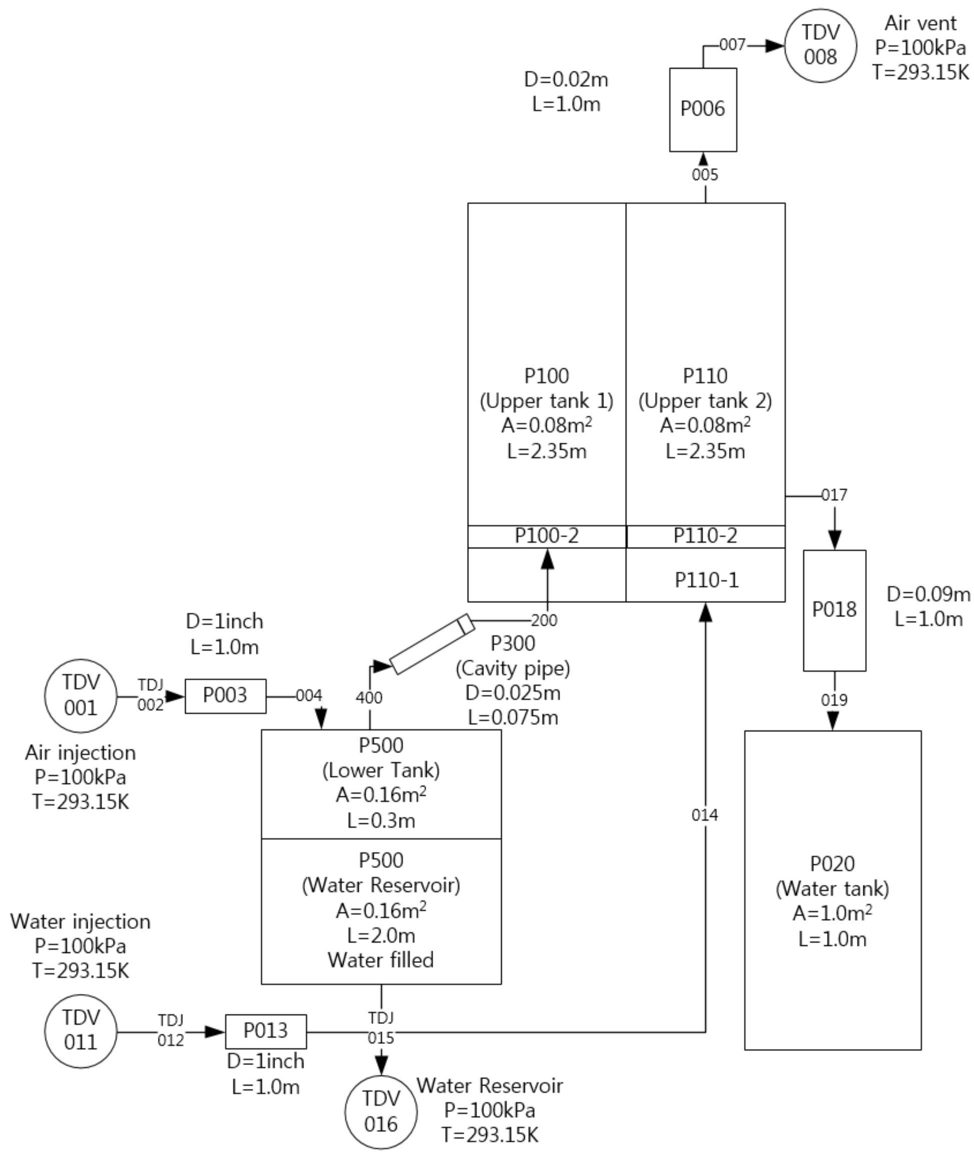

Figure 7. Nodalization diagram for the experimental apparatus of PASS-PECCS.

Fig. 8 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. 8, 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. 7. 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 and 1.2, respectively. (2) The forward and reverse form loss coefficient at the single junction 400 are 1.9 and 0.1, respectively. 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 [6]. Now, we are investigating the form loss coefficients at the water entrance and exit junction of the cavity pipe to obtain the coefficients without experiments

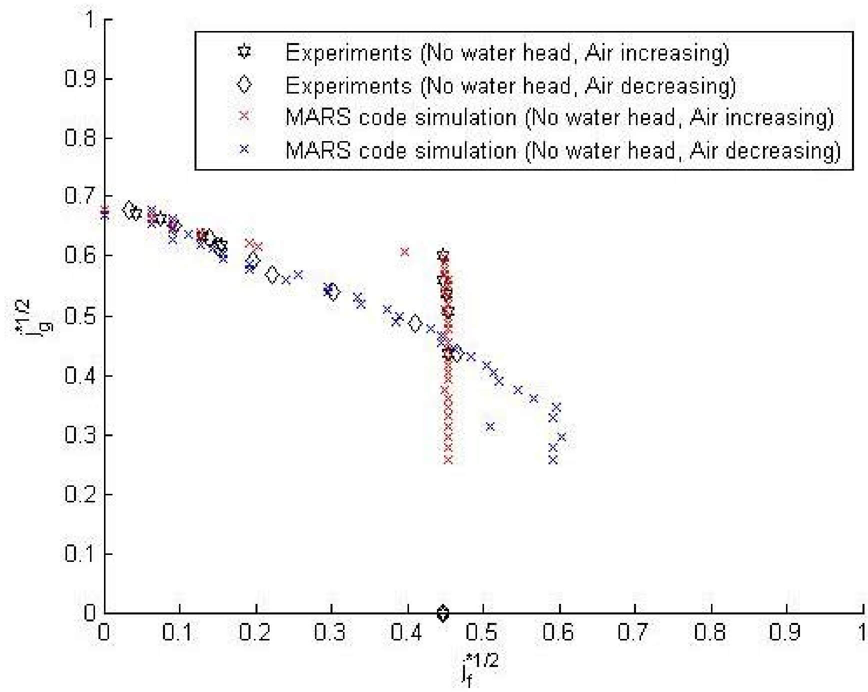

Figure 8. CCFL diagram of MARS code simulation and experimental results for no water head case.

4. CONCLUSIONS

The PECCS is the key safety system of the PASS system for removing decay heat passively and safely. CCFL is the most influential 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 that water head in upper tank enhances water penetration compared with no water head case and there is an optimal water head condition. 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.

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