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MARS-KS Code Analysis of the Pressure Wave test 0 performed at the PMK-2 test facility

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ABSTRACT

The pressure waves might be expected in the nuclear reactor systems due to sudden rupture of pipes, or quick opening or closure of the system valves. If generated, they can result in large mechanical loads on the RPV internal structures and pipelines, threating their integrity. This kind of phenomena is an important issue and a limiting accident case for the nuclear power plant safety, which requires extensive analysis to ensure nuclear power plant safety. To study these phenomena, four PWP (Pressure Wave Propagation) tests have been performed in the PMK-2 test facility in MTA EK. In addition, these tests have been used to assess the capability of the MARS-KS code in simulating the PWP phenomena. Then, an input model representing the PMK-2 test facility was developed to simulate the tests. The MARS-KS simulation results are then compared with the test results. The comparison shows that the MARS code can simulate the PWP frequencies and initial pressure peaks well. After the qualified assessment, the MARS-KS code is then deployed to conduct the sensitivity analysis on the effect of the break size, break time, coolant initial conditions on the PWP phenomena. The sensitivity analysis on the break sizes shows that the pressure wave amplitude is relevant to the break times: the shorter the break opening time is, the faster the pressure decreases. The sensitivity analysis on the break sizes shows that the larger the break size is, the higher the pressure peak is.

I. INTRODUCTION

If a pipe breaches suddenly in a nuclear system with high pressures, a depressurization wave can be generated and can propagate in the nuclear system at sonic speed. This sonic depressurization wave is called a shock wave, or pressure wave, which will be adopted in this paper. The generated pressure waves, which can be on the order of several bars, or more than 10 bars, can cause large mechanical loads on the RPV internal structures, then threating their integrity. Due to safety concerns, this research has been carried out.

The PWP phenomena have been studied and the abilities of some TH (Thermo-hydraulic) codes such as RELAP5 code [1] and WAHA3 code [2] to simulate the PWP phenomena have been assessed for a long time. Y. Takeda and S. Toda [3] conducted the PWP experiments to investigate the PWP phenomena in subcooled fluid with a temperature gradient. M. W. Wendel [4] verified the capability of the RELAP5 code in simulating PWP phenomena for an instantaneous pipe break through two tests: a single phase shock tube problem and a PWP test in a pipe with three sections of different flow areas. Later on, Jurgen Perlia [5] also applied the RELAP5 code to simulate the propagation of pressure waves in pipe systems for two cases: the feedwater trip and turbine valve trip transients. The capabilities of the RELAP5 code to predict the pressure wave propagation phenomena in single- and two-phase fluids are further demonstrated by Lukasz Sokolowski, et al [6]. The tests performed by Y. Takeda and S. Toda were simulated by Oriol Costa and Iztok Tiselj [7] using WAHA3 code, a one-dimensional code developed using the Method of Characteristics (MOC) for simulating water hammer and PWP phenomena.

Although the capabilities of the RELAP5 code and other specialized code such as WAHA3 code to simulate the PWP phenomena have been evaluated by the above mentioned authors by simulating some fundamental tests, few researches have been carried out to investigate the PWP phenomena in the loop-type systems which are of great interest and concern to the nuclear community for nuclear reactor safety.

In this research, the propagation of pressure waves in the loop-type system, the PMK-2 test facility has been studied for different cases with varying initial conditions and different break areas. In addition, some sensitivity analyses of the PWP phenomena on the break areas, break rupture times, and coolant initial conditions were performed using the MARS-KS code [8], a system TH code similar to RELAP5, developed by KAERI. Moreover, for the first time the MARS-KS code is employed to simulate the PWP test. Hence its capability in simulating PWP phenomena will be assessed.

II. SHOCK WAVE PROPAGATION TESTS

Since the PWP phenomena might be expected in the nuclear systems, it would be meaningful to conduct the PWP tests in the loop-type systems such as PMK-2 test facility to investigate these kinds of phenomena. Very few PWP tests were performed in the integral effect test facility representative of the nuclear power plants. The PWP tests performed in the PMK-2 test facility will address some concerns on the influence of the pressure waves on the nuclear reactor structures both internal and external. In addition, the PWP test would be used to assess the ability of several codes such as the MARS-KS code and the ATHLETE code in simulating the PWP phenomena

For the above purposes, several PWP tests, as summarized in **Table 1**, have been performed at the PMK-2 test facility as a part of the cooperative research program between KAERI (Korea) and MTA-EK (Hungary). These tests were performed to advance the understanding of PWP phenomena and to assess various thermo-hydraulic codes such as MARS-KS, RELAP5/MOD3.3, and WAHA3 code used in nuclear community. Further information on the test can be found in reference [9]. In the following, the PMK-2 test facility, the PWP test 0 and the simulation of the test using the MARS-KS code will be described.

Table 1. Test matrix

Parameter	**Unit**	**Test 0**	**Test 1**	**Test 2**	**Test 3**	**Test 4**
Primary sys. pressure	MPa	6.4	5.89	7.34	5.78	6.97
Core power	kW	20	0.	0.	0.	0.
Primary loop flow	kg/s	0.2	0.	0.	0.	0.
DC coolant temperature	^{o}C	231.0	210.9	220.8	226.	230.5
Pressurizer water level	m	9.01	9.04	9.11	9.11	8.98
SG water level	m	-	0.	0.	0.	0
Break orifice D_i	mm	8.0	6.0	6.0	8.0	8.0

II.A Test Facility PMK-2

The PMK-2 test facility as shown in **Fig. 1** is a one loop integral effect test facility representing the six-loop VVER440/213 type PWR (Pressurized Water Reactor) [10]. It is a full-pressure and full-height, but reduced-flow area model of the VVER440/213 type PWR. As the VVER440/213 type PWR which was developed by Russia has many special features different from the conventional PWRs, the PMK-2 facility was designed with these features incorporated. These special features include the horizontal SG (Steam Generators), the employment of hexagonal fuel assembly, and the injection of accumulator water from both DC and upper plenum. The power and volumetric scaling ratio of the PMK-2 facility to the VVER440/213 reactor is 1/2070.

The PMK-2 facility was designed to operate at full pressure and temperature conditions of the reference reactor in order to preserve the same coolant thermal conditions as in its reference reactor.

As shown in **Fig. 1**, the PMK-2 test facility, similar to the VVER440/213, consists of a RPV (Reactor Pressure Vessel), a loop with hot leg and cold leg, a horizontal SG, a RCP (Reactor Coolant Pump), and a set of ECCS (Emergency Core Cooling System). The ECCS is made up of one HPSI (High Pressure Safety Injection) system connected to the cold leg, one LPSI (Low Pressure Safety Injection) system connected to the UP, and two accumulators connected to the DC and UP, respectively. A more detailed description of the test facility can be found in reference [11].

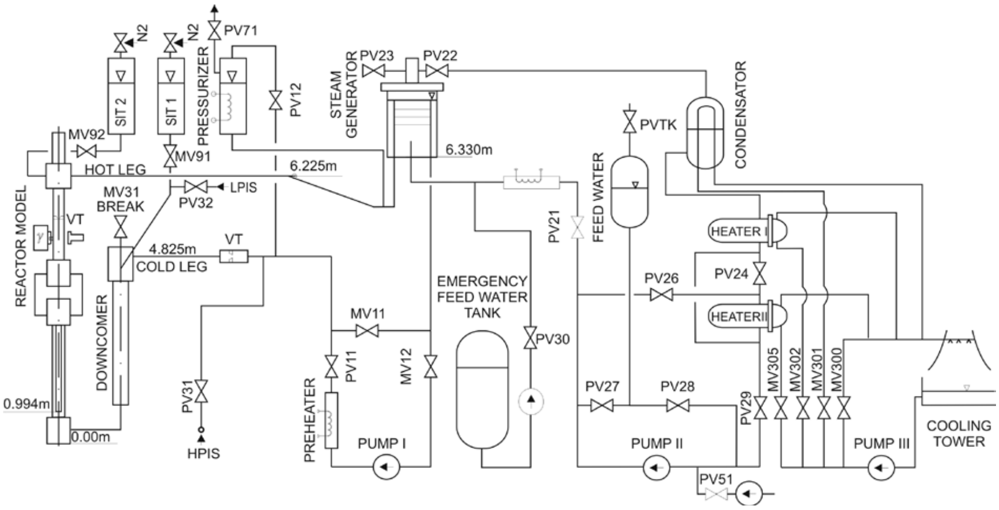

Figure 1 Schematic of the PMK-2 test facility

The pressure waves can be generated by quickly opening the break valve on the PMK-2 test facility. Since the PMK-2 can be operated at the nominal pressure and temperature of the reference reactor VVER440/312, the pressure waves generated would be the same order of magnitude as in the general NPP. The phenomena produced in the PMK-2 test facility would be similar to those in the NPPs. The data obtained would be very useful for evaluating the effect of the pressure waves on the reactor structures.

II.B Overview of the PWP Test 0

The test conditions of the PWP test 0 are given in **Table 1**. The test is a simulation of a small break LOCA due to break of a pipe at the DC (Downcomer). The inner diameter of the orifice simulating the break is 8 mm. The test was performed at an initial pressure of 64 bar, and initial DC temperature of 231 ^{o}C. The pressurizer initial water level is 9.01 m relative to the RPV bottom. In addition, the SG was initially filled with some saturated water. The break was initiated in milliseconds so that the pressure waves could be generated in the loop.

Here, the test results are mainly used as a PWP test to evaluate the capability of the MARS-KS code in simulating the PWP phenomena, and to assess the correctness of the input model in simulating the PMK-2 test facility.

II.C Simulation of the PWP Test 0

For the simulation of this test using MARS-KS code, an input model that models all necessary geometries and TH conditions of the PMK-2 test facility was developed based on the input model developed by MTA-EK. The nodalization of the PMK-2 test facility for MARS-KS code modeling is shown in **Fig. 2**. MARS-KS code is a system TH code developed at KAERI by consolidation of the COBRA-TF code for 3-D modeling of the RPV and the RELAP5/MOD3.3 code for one-dimensional modeling of the system. Thus, it has features of both codes. However, for this study, only the one-dimensional system modeling feature was used.

The same test conditions as given in **Table 1** for the test 0 were implemented in the input model. The simulated results with the MARS-KS code are compared with the test results in the following. The transients of the pressures in the lower plenum, upper plenum and downcomer are shown in **Fig. 3**. It is shown that the initial decrease rates of the pressures are almost exactly reproduced by the MARS-KS code, and thus are the first negative pressure peaks. However, the pressure transients after 0.04 s recovered faster in the simulation, which results from the incorrect modeling of the PRZ flashing behavior (the PRZ surgeline reverse flow), as shown in **Fig. 4**. Generally, the pressure can recover if the PRZ surgeline flow exceeds the break flow, as explained and demonstrated in [3]. **Fig. 4** and **Fig. 5** show the Differential Pressures (DP) between LP and Upper Plenum (UP), and between DC and UP, respectively. The initial DP peaks between LP and UP, and between DC and UP, are almost exactly reproduced by the simulation. As the first DP peak is the largest, it is most critical to the integrity of the internal structure. In addition, the general frequency of the PWP for these two DPs is also satisfactorily simulated.

From the above comparisons, it is seen that MARS-KS code can simulate the initial pressure wave magnitude and initial PWP frequency with satisfactory accuracy. Thus, it is concluded that the MARS-KS code is capable of simulating PWP phenomena.

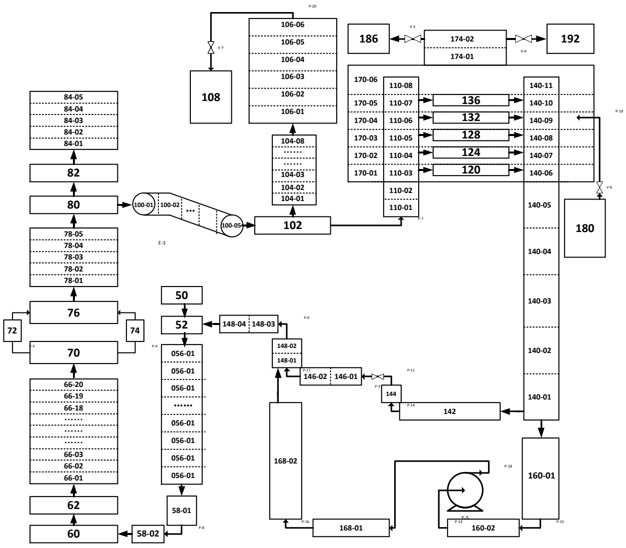

Figure 2 Nodalization for the PMK-2 test facility

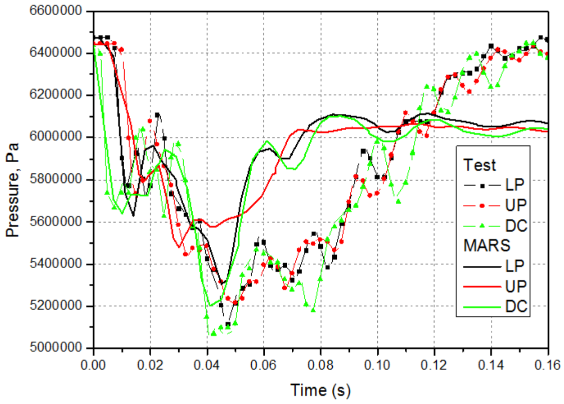

Figure 3 Transients of pressures in the lower plenum, upper plenum and downcome

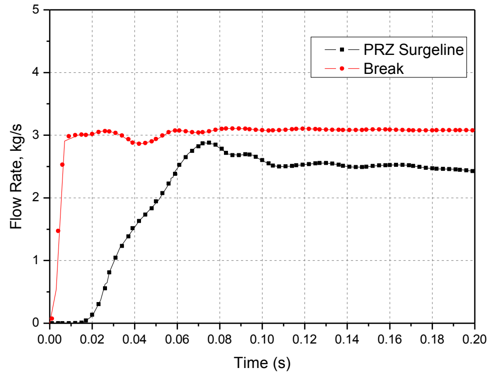

Figure 4 Transients of PRZ surgeline flow and break flow

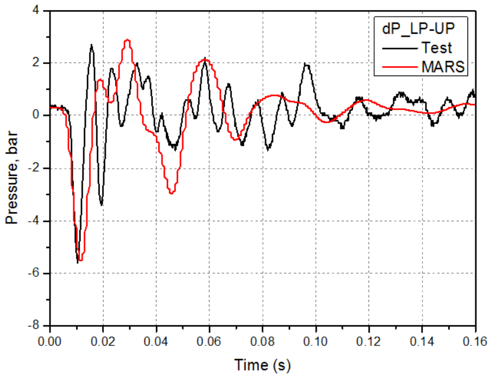

Figure 5 Differential pressures between lower plenum and upper plenum

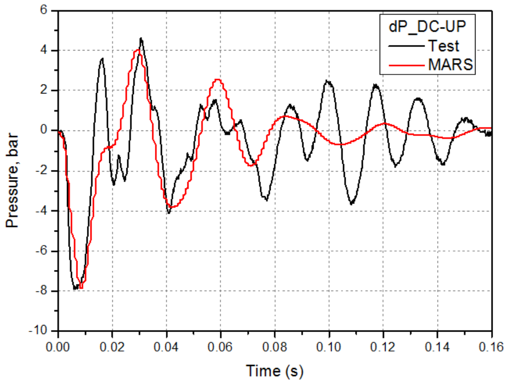

Figure 6 Differential pressures between down-comer and upper plenum

III. SENSITIVITY ANALYSES

Since the MARS-KS code can simulate the PWP phenomena quite well, especially the initial stages of the phenomena which are most critical from the viewpoint of safety concerns, it would be very meaningful to conduct some sensitivity analyses of the PWP phenomena using the MARS-KS code. In the following, the effect of the break sizes, break rupture times, and coolant initial conditions on the PWP phenomena are studied.

With the validated input model, the sensitivity of the pressure wave propagation on the break sizes, break rupture times and the coolant initial pressures are further investigated. The sensitivity analysis matrix is given in **Table 2**. Three break sizes simulated with orifice inner diameters of 6 mm, 8 mm and 10 mm are assumed; three break times of 5 ms, 10 ms and 50 ms are analyzed; and the initial pressures of 64 bar, 80 bar and 100 bar are assumed with a subcooling of 49 °C. The test conditions marked in bold are selected as the base case conditions.

Table 2 Sensitivity analysis matrix

Di, mm	**A, m^2**		**Rupture time, s**	**Pressure, bar**
6	2.83E-05		0.005	
8	**5.03E-05**		**0.01**	**64**
10	7.85E-05		0.05	80
				100

III.A Effect of Break Areas

The break sizes are considered as an influencing parameter affecting the PWP phenomena, because they are related to the break flow rate, hence affecting the pressure wave magnitude. For the sensitivity analysis, the test conditions of the initial pressure of 64 bar, break valve opening time of 0.01 s, and break area with an orifice of an inner diameter of 8 mm are defined as the base case conditions. Three different break sizes with nozzle diameters of 6 mm, 8 mm, and 10 mm are assumed for the sensitivity analysis.

In all calculations, the same base case conditions are applied except different break sizes as given in **Table 2**. **Fig. 7** shows the DC pressure transients for the three different break sizes. As shown, the larger the break size, the faster the pressure decrease rate, and the deeper the negative pressure peak. As shown in **Fig. 8** for the transients of DP between the DC and the UP, and in **Fig. 9** for the transients of DP between the LP and the UP, the larger the break size is, the higher the pressure wave magnitude. From the results, it is concluded the break size has a large effect on the pressure wave magnitude, but no effect on the wave frequency.

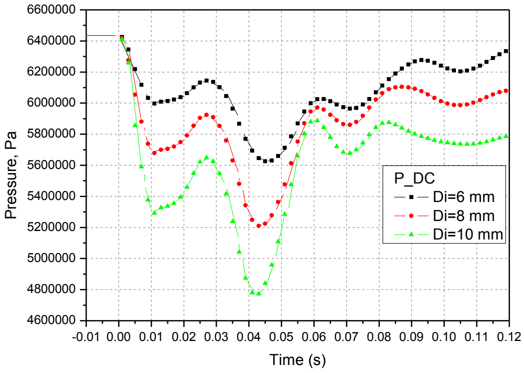

Figure 7 Pressures in the downcomer for the different break sizes

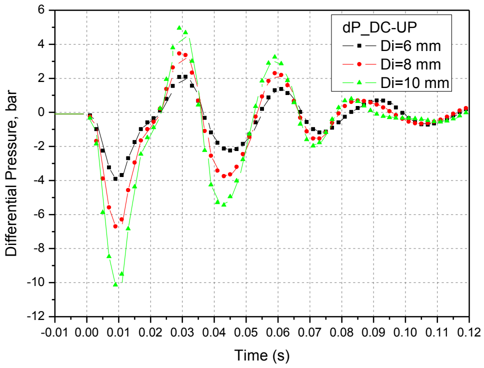

Figure 8 Differential pressures between the DC & UP

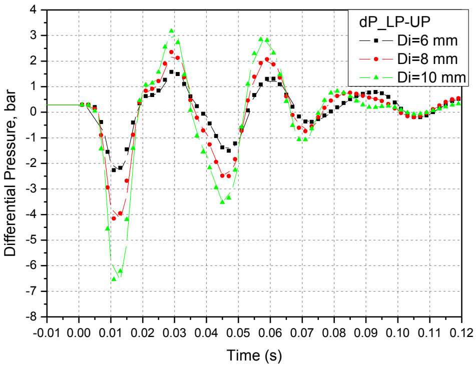

Figure 9 Differential pressures between the LP & UP

III.B Effect of Pipe Rupture Times

The effects of the break rupture times have already been observed in the PWP tests performed. Here, some sensitivity analyses of PWP phenomena on the ruptures times are performed to confirm the observations.

In all calculations, the same base case conditions are applied except the break rupture times as given in **Table 2**. Three break times of 0.005 s, 0.01 s and 0.05 s are applied. The transients of the pressures in the DC for the three cases are shown in **Fig. 10**. It shows that the time to reach the first pressure peak is the same as the break rupture time. **Figure 11** shows the differential pressures between the DC and UP. The results imply that the faster the break occurs, the higher the pressure wave magnitude is. This means the break time has also a large effect on the pressure wave propagations.

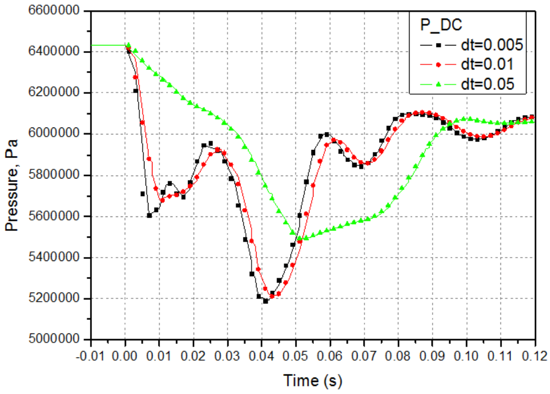

Figure 10 Pressures in the downcomer for the different break times

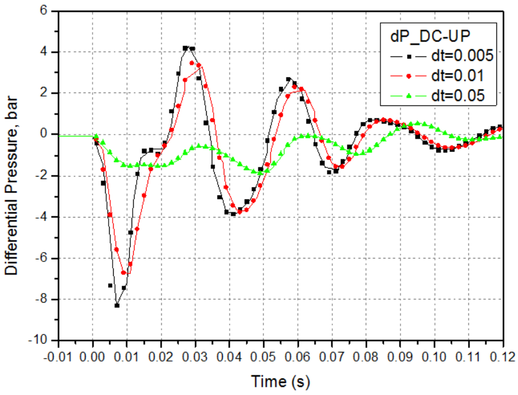

Figure 11 Differential pressures between the DC & UP

III.C Effect of Initial Pressures

Again, the same base case conditions except the initial pressures are assumed for three cases to perform the sensitivity analyses. In all calculations, the same base case conditions are applied for the three cases except that different initial pressures of 64 bar, 80 bar, and 100 bar are assumed for each case. The calculated results are presented and discussed in the following.

Figure 12 shows the transients of DC pressures for the three cases. The initial pressures are different as specified. However, the times to reach the negative pressure peak are the same for the three cases, as the same valve opening time of 0.01 s is assumed for each case. The results again confirm that the times to reach the first negative pressure peak are relevant to the break rupture times. The differential pressures between DC and UP and those between LP and UP are shown in **Fig. 13** and **Fig. 14,** respectively. As shown, the initial coolant pressures have a very limited effect on the pressure wave amplitudes, much smaller than the effects of the break sizes and the break rupture times.

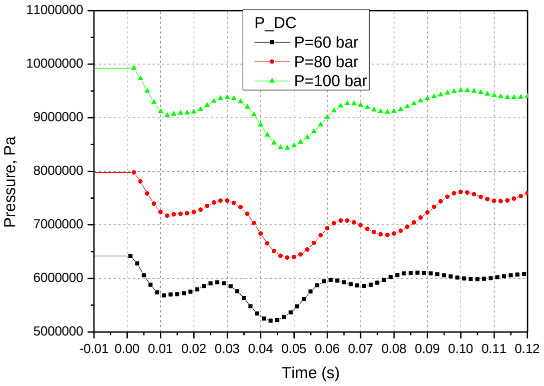

Figure 12 Pressures in the downcomer

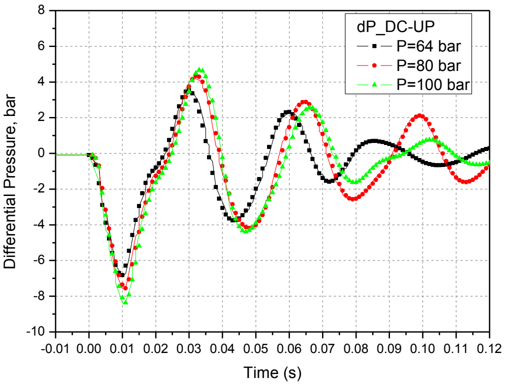

Figure 13 Differential pressures between the DC & UP

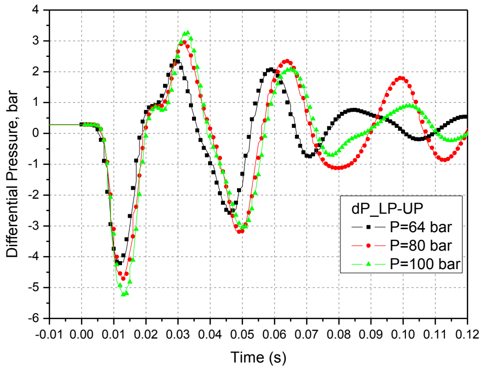

Figure 14 Differential pressures between the LP & UP

IV. CONCLUSIONS

As part of the cooperative research program between Korea and Hungary to study the PWP phenomena, a PWP test has been used to evaluate the capability of the MARS-KS code in simulating the PWP phenomena.

Prior to the sensitivity analysis, a previous PWP test named test 0 has been simulated by the MARS-KS code. The simulation reproduces quite well the first negative pressure peak and the first negative differential pressure peak. Thus, it was concluded that the MARS-KS is capable of simulating the PWP phenomena, particularly the initial phase. Then, the well validated input was used to perform some sensitivity analysis of the PWP on the break sizes, break times, and initial coolant conditions. It was found that both break sizes and break times have a large effect on the PWP amplitudes. What is more, the time to reach the first negative pressure peak was found to be relevant to the break rupture time. In addition, the sensitivity analyses demonstrate that the coolant initial pressure has very limited effect on the pressure amplitudes.

Since the pressure waves are related to the break rupture times or the valve opening times, and the pressure wave amplitudes increase considerately with a break rupture time of less than 0.05 s, it is suggested that the valve opening time should be larger than 0.05 s in order to minimize the pressure wave effect due to a sudden opening of the valves in the nuclear system. In addition, the obtained results can be further used to conduct the stress analyses of the reactor core internal structures to see whether the pressure waves have a critical impact on the integrity of the reactor core internal structures.

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