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Supercritical Water Flow Model of the SPACE Code and Its Verification

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1. Introduction

In the most of normal operation conditions, transients, and even the postulated accidents, the reactor coolant system (RCS) in typical pressurized water reactors (PWRs) remains well below the critical pressure of water. However, in the cases of some beyond design base events (BDBE) such as anticipated transients without scram (ATWS), the RCS pressure might become higher than the critical pressure in a certain period of the events. Moreover, because the efficiency of a power plant is ultimately dependent on the temperature difference between heat source and sink, some effort has been made to develop Generation IV reactors operated by the working fluid at a higher pressure and temperature. The supercritical water reactor (SCWR)[1] is one of the examples. Therefore, it is useful for a light water reactor system safety analysis code to have a supercritical water flow model. In this paper, the supercritical water flow model implemented in the Korean PWR system safety analysis code, SPACE[2], and its verification test results are presented.

2. Supercritical Fluid Model

In the SPACE code, the three-field governing equations with the source terms representing the phase changes are simultaneously solved under the assumption that the interface temperature is maintained at the saturation temperature. However, in the supercritical condition, where the liquid and vapor phases disappear and they become a single supercritical phase, the phasic volume fractions of the continuous liquid, dispersed liquid, and the vapor phases are meaningless. The phase change models do not work either. Therefore, it is necessary to develop a single supercritical fluid flow model separately from the three-field-equation based two-phase flow model or to modify the two-phase flow model to extend its application range to the supercritical condition. In the supercritical water flow model of the SPACE code, the meaningless concept of three phases is still used. Instead, the phase change is prohibited in the supercritical condition, so that the phasic volume fractions can remain as they were at the last subcritical condition. Phase change is suppressed by 1) giving zero value to the interfacial heat transfer coefficients, entrainment and de-entrainment rates, and wall vaporization sources, and 2) setting the saturation temperature, saturation liquid and vapor enthalpies to be at the thermodynamic condition of the critical point. Further effort is still necessary in order for the supercritical water flow model based on the three-field equations to simulate more realistic supercritical flow condition. For example, further study may be necessary on the following technical area.

1) More reasonable phasic volume fraction for the supercritical fluid needs to be estimated depending on the pressure and temperature, so that the supercritical fluid can be easily separated into three-fields when it returns to subcritical condition,
2) Some experimental correlations such as wall heat transfer coefficient and wall friction need to be checked to be still valid in the supercritical condition.
3) A methodology to enhance the interfacial heat and momentum transfer needs to be developed for the purpose of homogenization of the meaningless three phases.

However, the simple model of supercritical water flow in the current version of the SPACE code is focused only on its prime objective, i.e., prevention of code failure while the system pressure increases beyond the critical pressure. Another requirement of the SPACE supercritical flow model is that the supercritical fluid should be separated into three-fields and settle down at the two-phase equilibrium condition, when returning to a subcritical condition. Although the change rate of the phasic volume fraction may not be always smooth at the critical point, the interfacial heat transfer is expected to induce appropriate mass transfer between the phases and to redistribute the supercritical fluid into liquid and vapor phases with their proper volume fractions, depending on phasic energies.

3. Test Results

3.1 Test Problem

As mentioned earlier, the current version of supercritical flow model in the SPACE code is designed only to avoid code failures during analyzing BDBEs where the system pressure can be above the critical pressure in a certain time period of the events. Some models and correlations, and the initialization processes are not modified yet sufficiently enough to model the supercritical flow and heat transfer. Consequently, possible test problems are restricted to the range where initial and boundary conditions are not the supercritical state but remain subcritical. Therefore, a vertically aligned cylindrical tank is chosen as a conceptual test facility. The cylindrical tank is initially filled with vapor or liquid, or partially filled with liquid. Then, single or two-phase flow is injected at the bottom until the tank pressure increases beyond the critical pressure, and then drained until the system pressure returns to a subcritical condition.

3.2 Results

In the first test case, the tank is initially filled with the saturated vapor at 155 bars. When the test starts, vapor is injected at the bottom for about 50 seconds, and then the boundary flow condition changes its direction to result in outflow from the tank. The tank pressure approaches critical condition at around 20 seconds, and the pressure increases further beyond the critical pressure which is about 220 bars. The previous version of SPACE code, in which the supercritical flow model is not incorporated, failed to run when the system pressure exceeds the critical pressure. On the other hand, the present version of the SPACE code succeeds to run even in the pressure range above the critical point, by virtue of the supercritical flow model. As shown in the figure, the returning process to the subcritical condition is also successful.

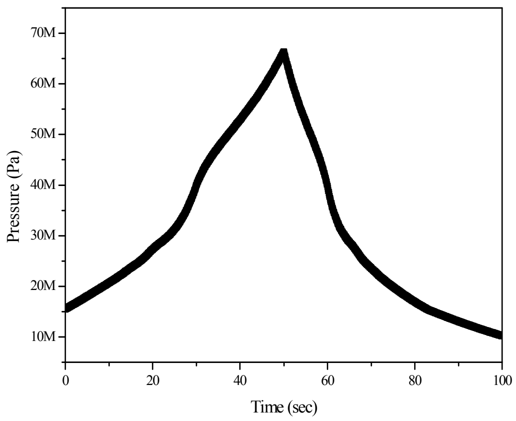

Figure 1. Pressure variation during the test case 1

In second test case, the lower half of the tank is filled with the saturated liquid at 155 bars, and the remaining upper half region is filled with the saturated vapor at the same pressure. For the first 160 seconds, two-phase flow with void fraction, 0.5, is injected into the tank. And the two-phase mixture flows out from the bottom nozzle for the rest period of the test. In this case, the SPACE code also runs successfully for the whole test process consisting of the pressure excursion and return to the subcritical condition.

4. Conclusions

A supercritical flow model has been incorporated into the SPACE code. Although the present model is still not accurate sufficiently to model the realistic fluid flow and heat transfer in the supercritical condition, it is found to be useful to prevent the code failure even in the high pressure range above the critical point. The SPACE supercritical flow model works also properly, when the system pressure returns to a subcritical condition.

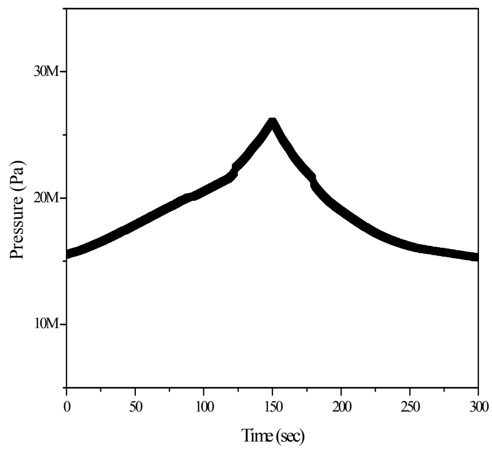

Figure 2. Pressure variation during the test case 2

Consequently, it is expected that the SPACE supercritical flow model is applicable to the beyond design base events which might result in severe pressurization in a certain period of the events

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