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Additional Model Datasets and Results to Accelerate the Verification and Validation of RELAP-7

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NOTICE

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ABSTRACT

The RELAP-7 code verification and validation activities are ongoing under the code assessment plan proposed in the previous document (INL-EXT-16-40015). Among the list of V&V test problems in the 'RELAP-7 *code V&V RTM (Requirements Traceability Matrix)*', the RELAP-7 7-equation model has been tested with additional demonstration problems and the results of these tests are reported in this document. In this report, we describe the testing process, the test cases that were conducted, and the results of the evaluation.

CONTENTS

FIGURES

ACRONYMS

INL	Idaho National Laboratory
MOOSE	Multi-Physics Object Oriented Simulation Environment
RTM	Requirements Traceability Matrix
V&V	Verification and Validation

Additional Model Datasets and Results to Accelerate the Verification and Validation of RELAP-7

1. INTRODUCTION

RELAP-7 is a nuclear thermal-hydraulic system analysis code under development within MOOSE framework by Idaho National Laboratory (INL) [1]. As a part of the software quality assurance, INL has a project to establish an independent code assessment plan for RELAP-7 called RELAP-7 Software V&V Plan [2]. The main purpose of this plan is to provide a suitable way to evaluate and document the RELAP-7 development status as well as the code prediction capability so that the final code product quality can be assured through the development process. In the INL document for the RELAP-7 code assessment plan [2], the various aspects of requirements for RELAP-7 are identified through the review of legacy code manuals, system code users' experience, and nuclear industry needs. Also, the document provides the necessary information that can be used for the RELAP-7 assessment, including the specific list of V&V test problems, in a form of matrix, i.e., Requirements Traceability Matrices (RTM). As a result, this plan can be used to keep track of the RELAP-7 development status and is expected to help the RELAP-7 assessment and/or V&V process to be more effective and systematic.

At present, RELAP-7 assessment activity is ongoing by INL within the framework established in the RELAP-7 Software V&V Plan [2]. In this document, the recent activities of the verification and validation of RELAP-7, performed by the independent INL RELAP-7 code assessment team, are described. Specifically, the RELAP-7 version as of 2016 has been tested with additional V&V test problems adopted from the 'RELAP-7 *code V&V RTM'*; the test results, issues found, and related discussion are reported.

2. TEST PROBLEMS AND TEST RESULTS

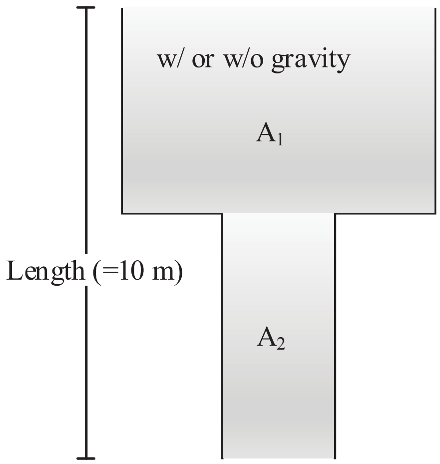
Among the list of V&V test problems in the 'RELAP-7 *code V&V RTM*' [2], three verification tests (Requirement ID: VR-1, VR-2, VR-3) and two validation tests (Requirement ID: VR-19, VR-35) are conducted. In this section, the test results along with the issues found are discussed.

2.1 Verification Tests

2.1.1 Single-phase analytical test without flow (Verification problem 1)

This is a demonstration problem to verify the function of the 7-equation model in RELAP-7 at hydrostatic condition. Uniform pressure, zero velocity, single-phase (α_{vap}=10^{-4}), and spatially varying cross-sectional area are imposed as initial conditions, as shown in Figure 1. Also, no external forces but gravity are taken into account. Considering the physics, the flow velocity of both phases should remain zero through the simulation as a result of balanced forces (*e.g.*, gravity, pressure gradient).

Figures 2 and 3 show the simulation results without and with gravitational effect, respectively. With no effect of gravity (Figure 2), the flow velocities of both phases remain zero and no pressure fluctuation is found during the simulation (simulation time: 75 [sec]). On the other hand, once gravity is considered, the velocity of vapor phase fluctuates upto about 0.03 m/s in the middle section of pipe as shown in Figure 3 (left side) while the liquid velocity remains zero until the end of simulation. This implies that there exists unbalance between the gravity and the pressure gradient forces for the vapor phase. It is also noted that the tiny value of α_{vap} (10^{-4}) applied to this problem may have affected such fluctuation of vapor velocity shown in Figure 3 (note $u_k = \frac{< X_k \rho_0 u_0 >}{\alpha_k \rho_k}$, see [1]).



[Initial Condition]
$u_{liq}=u_{vap}=0$ [m/s], $p_{liq}=p_{vap}=1e5$ [pa]
$\alpha_{vap}=1e-4$ (nearly single-phase)
$A_1=1.9e-4$ [m^2], $A_2=0.9e-4$ [m^2], L=10 [m]

[Boundary Condition]
SolidWall (both inlet and outlet)

[Stabilizations]
EntropyViscosity

Figure 1. Test conditions for the verification problem 1

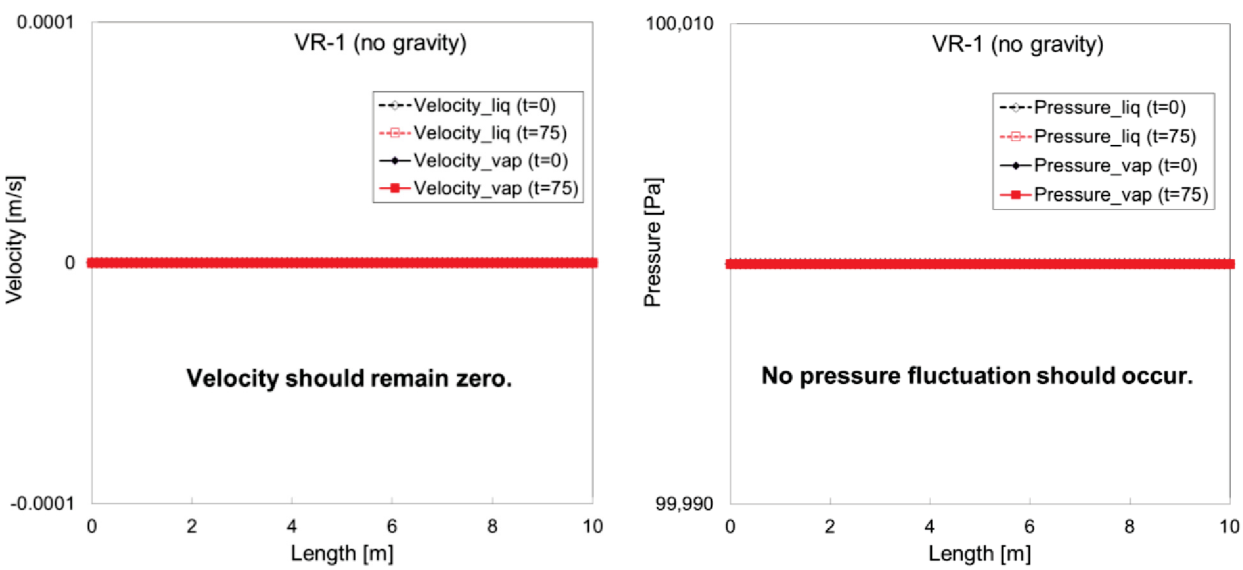
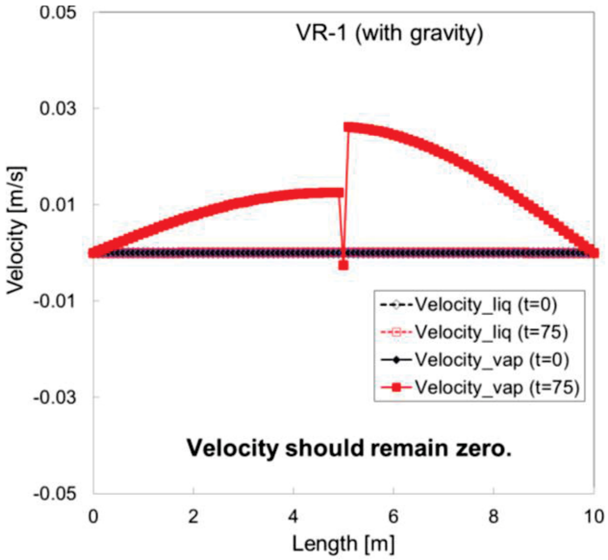


Figure 2. Velocity (left side) and pressure (right side) at the beginning and end of simulation (no gravity)



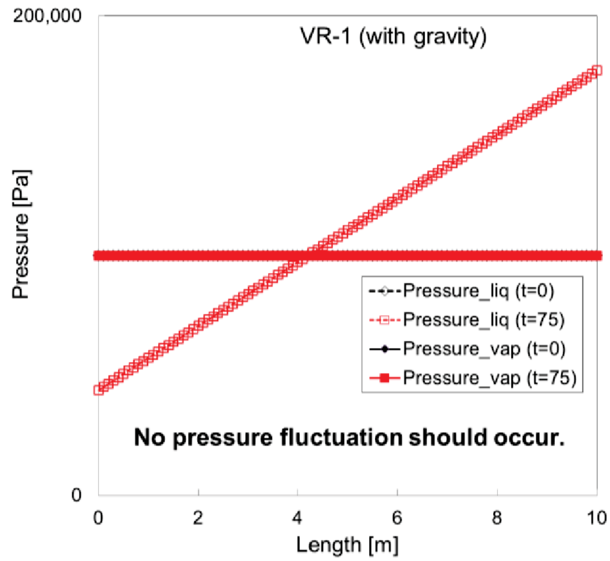
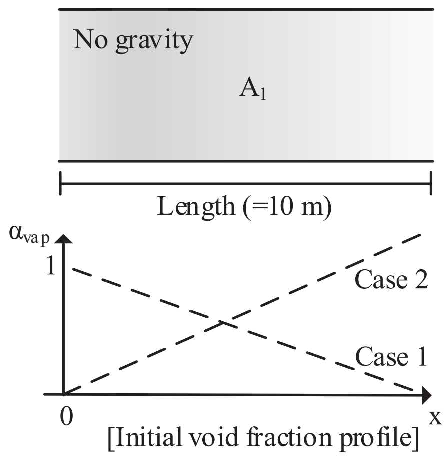


Figure 3. Velocity (left side) and pressure (right side) at the beginning and end of simulation (with gravity)

2.1.2 Single-phase analytical test without flow (Verification problem 2)

This is a second demonstration problem to verify the 7-equation model of RELAP-7 at hydrostatic condition. Uniform cross-sectional area, two-phase, and spatially varying volume fraction profile are imposed as initial conditions. Also, no gravitational effect is considered for this test. The specific initial and boundary conditions are summarized in Figure 4. The test is performed with two initial volume fraction profiles (*i.e.*, Case 1: linearly-increasing volume fraction, Case 2: linearly-decreasing volume fraction). Physically, the flow velocity of both phases should remain zero due to balanced forces while the volume fraction profile as well as pressure along the pipe should remain constant without fluctuation.

Figure 5 shows that the initially given volume fraction profile is well maintained for the both test cases through the simulation (simulation time: 75 [sec]). Also, the flow velocities of both phases remain zero and no fluctuation is found for the pressure as shown in Figure 6.



[Initial Condition]
$u_{liq}=u_{vap}=0$ [m/s], $p_{liq}=p_{vap}=1e5$ [pa]
α_{vap}=linear profile ('Case 1' or 'Case 2' , two-phase)
$A_1=1.9e\text{-}4$ [m^2], L=10 [m]

[Boundary Condition]
SolidWall (both inlet and outlet)

[Stabilizations]
EntropyViscosity

Figure 4. Test conditions for the verification problem 2

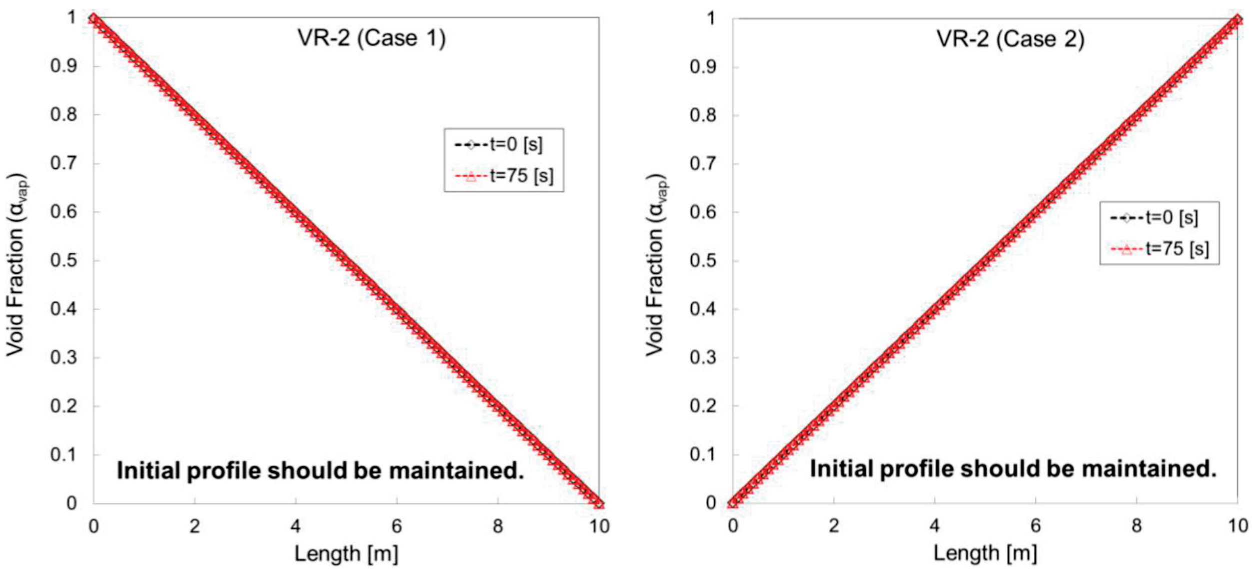


Figure 5. Void fraction profile along the pipe at the beginning and end of simulation

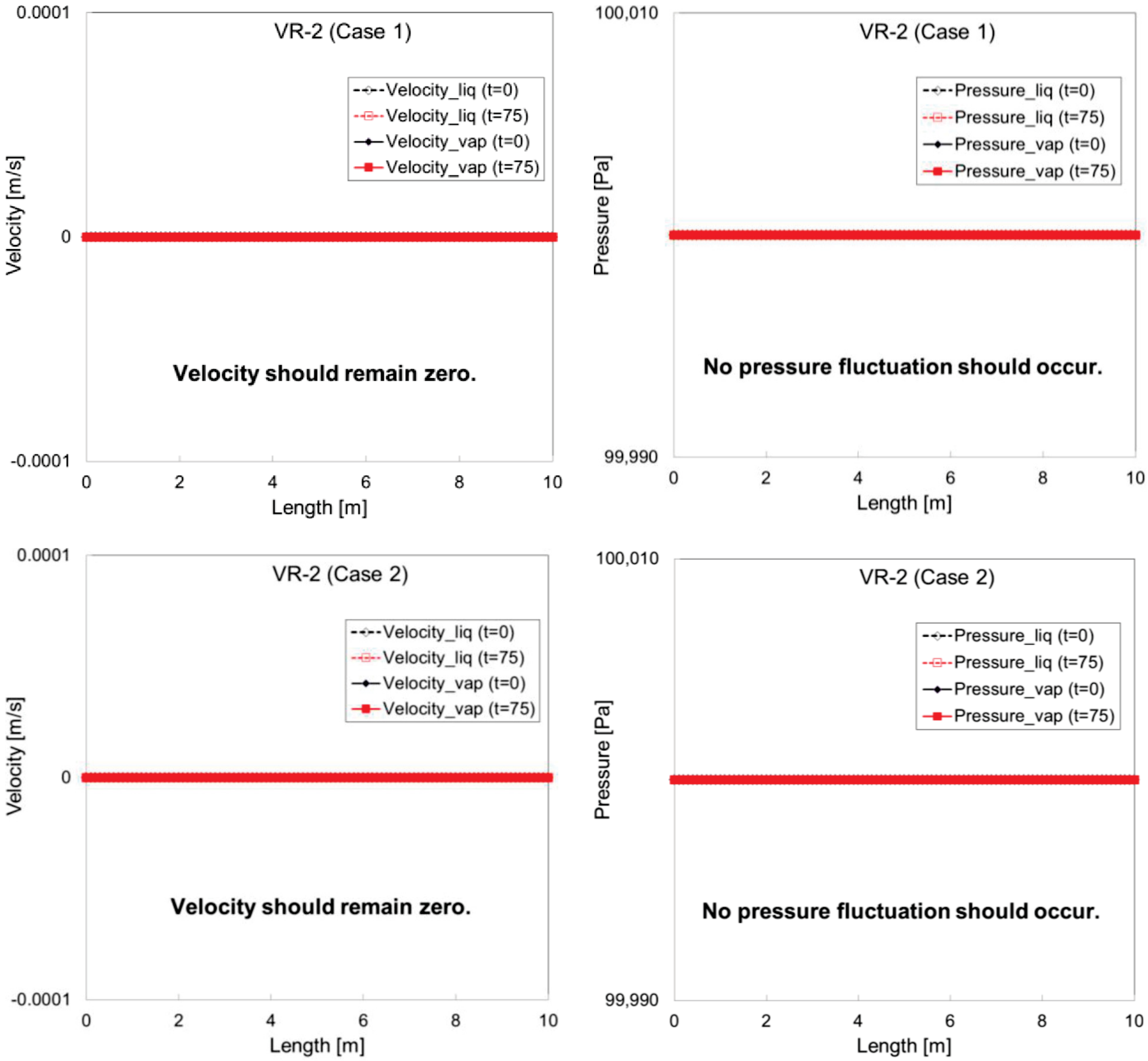
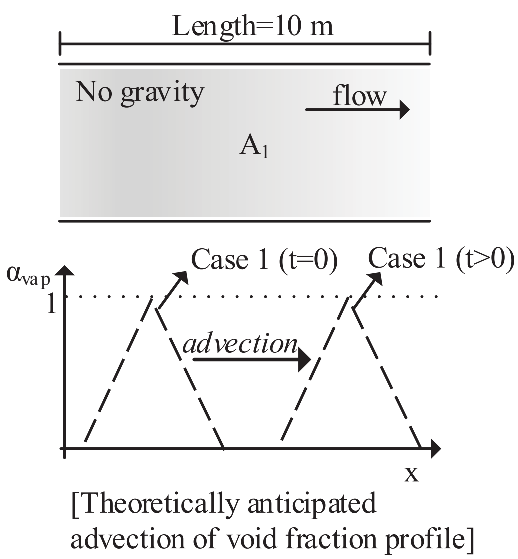


Figure 6. Velocity (left column) and pressure (right column) along the pipe at the beginning and end of simulation for Case 1 and Case 2

2.1.3 Two-phase analytical test for volume fraction advection (Verification problem 3)

This case represents an analytical test to verify the function of 7-equation model for volume fraction advection. With initially given uniform pressure and velocity as well as a spatially varying volume fraction, the volume fraction profile should simply advect with simulation time while the pressure and velocity field remains uniform. The initial and boundary conditions utilized for this test problem are summarized in Figure 7. No gravitational effect is considered. This test is conducted with three different initial volume fraction profiles, the results of which for the two tests (Case 1 and Case 3) are presented in this section.

The ‘Case 1’ test is performed with initially-given volume fraction profile (α_{vap}) varying between 0 and 1 as shown in Figure 8 (left side at t=0). The left side of Figure 8 shows the advection of the volume fraction profile as simulation time passes. However, the void fraction profile in Figure 8 is deformed as it is advected which is likely due to the numerical dissipation (note that the first-order entropy viscosity method is utilized for this test problem for solution stabilization). Specifically, the maximum value of the volume fraction (initially $\alpha_{vap,max}$=1) is decreased with time while the shape of the volume fraction profile is diffused. Also, it is important to note that the code stopped at about t=80 [sec] for this ‘Case 1’ test. This is closely related to the fact that the negative value of volume fraction, *i.e.*, undershooting α_{vap} occurs at about t=80 [sec] (see the right side of Figure 8). Figure 9 also shows that both the vapor velocity and the vapor pressure significantly fluctuate at the corresponding time. This implies the undershooting of the volume fraction below 0 caused the code stability issue with significant fluctuation of vapor pressure and velocity. To confirm this conclusion, another test ‘Case 3’ is conducted with different initial volume fraction profile varying between 0.2 and 0.8, shown in Figure 10. In this additional case, it was found that the code ran without failures although the numerical dissipation is still observed as the volume fraction is advected. In addition, Figure 11 shows that the flow velocity and the pressure of both phases remain uniform during the simulation (the fluctuation of vapor velocity shown in Figure 11 is less than 0.002%).



[Initial Condition]
$u_{liq}=u_{vap}$=0.1 [m/s], $p_{liq}=p_{vap}$=1e5 [pa]
α_{vap}= spatially varying (Case 1-Case3)
A_1=1.9e-4 [m^2], L=10 [m]

[Boundary Condition]
inlet: Inlet ($u_{liq}=u_{vap}$=0.1 [m/s], $p_{liq}=p_{vap}$=1e5 [pa])
outlet: Outlet ($p_{liq}=p_{vap}$=1e5 [pa])

[Stabilizations]
EntropyViscosity

Figure 7. Test conditions for the verification problem 3

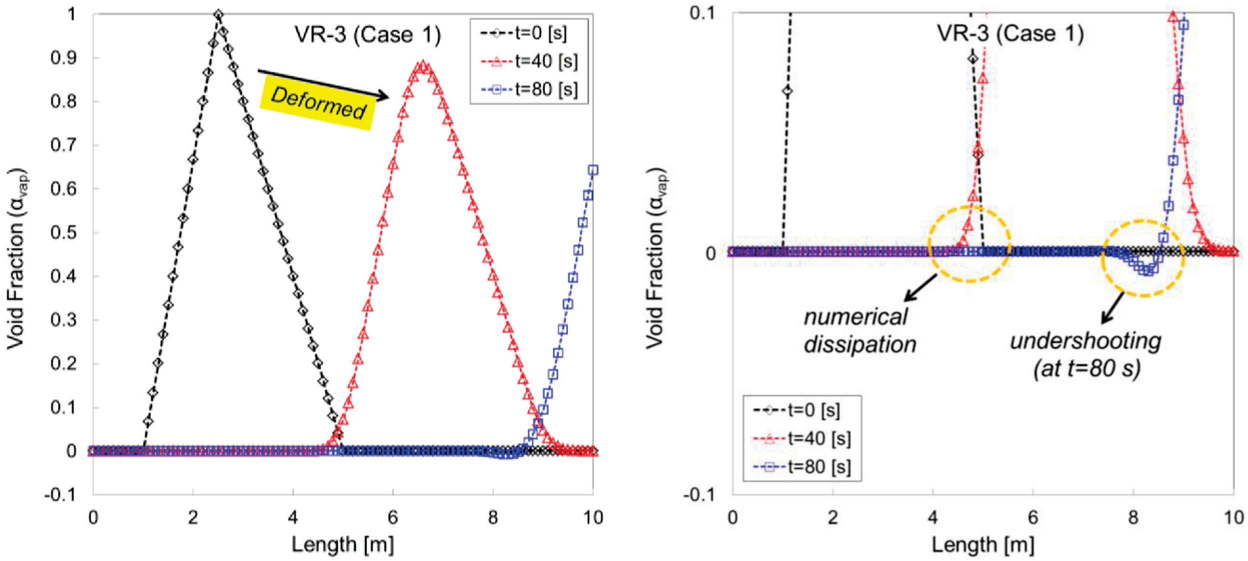


Figure 8. Advection of void fraction profile along the pipe for Case 1

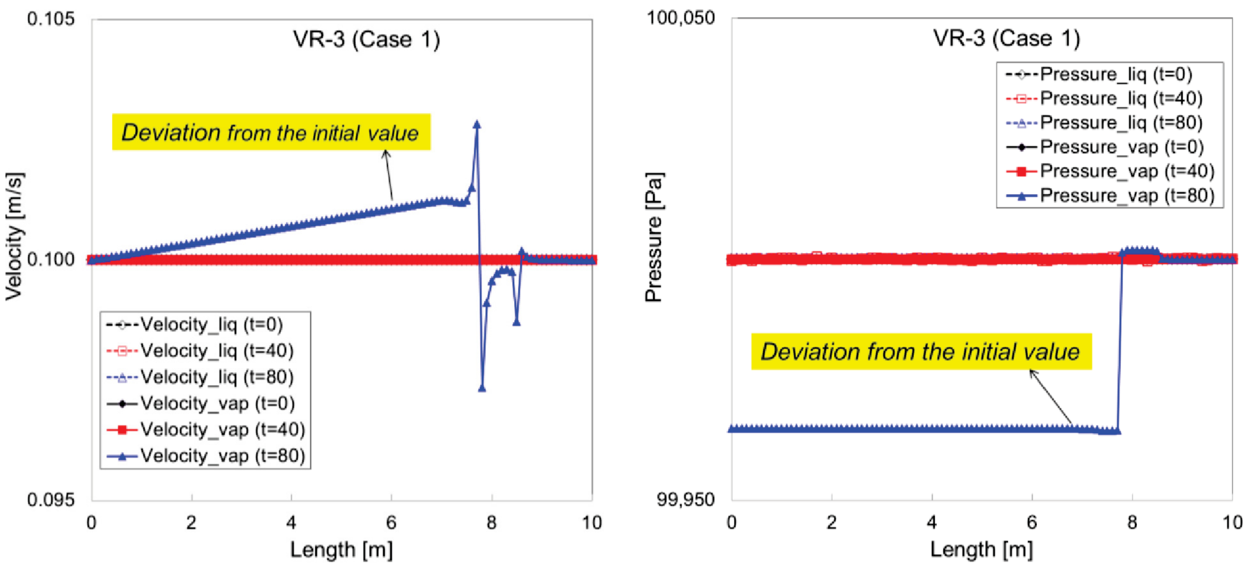


Figure 9. Velocity (left side) and pressure (right side) along the pipe for Case 1

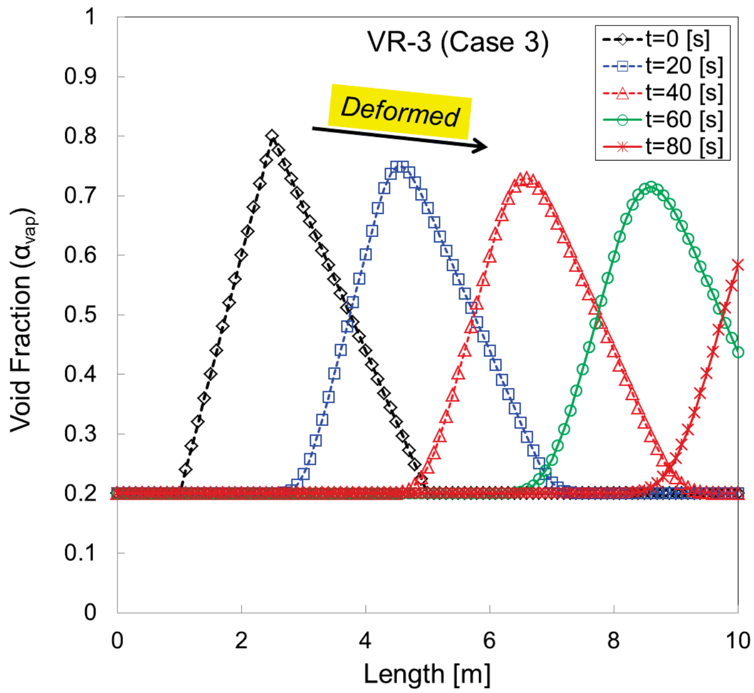


Figure 10. Advection of void fraction profile along the pipe for Case 3

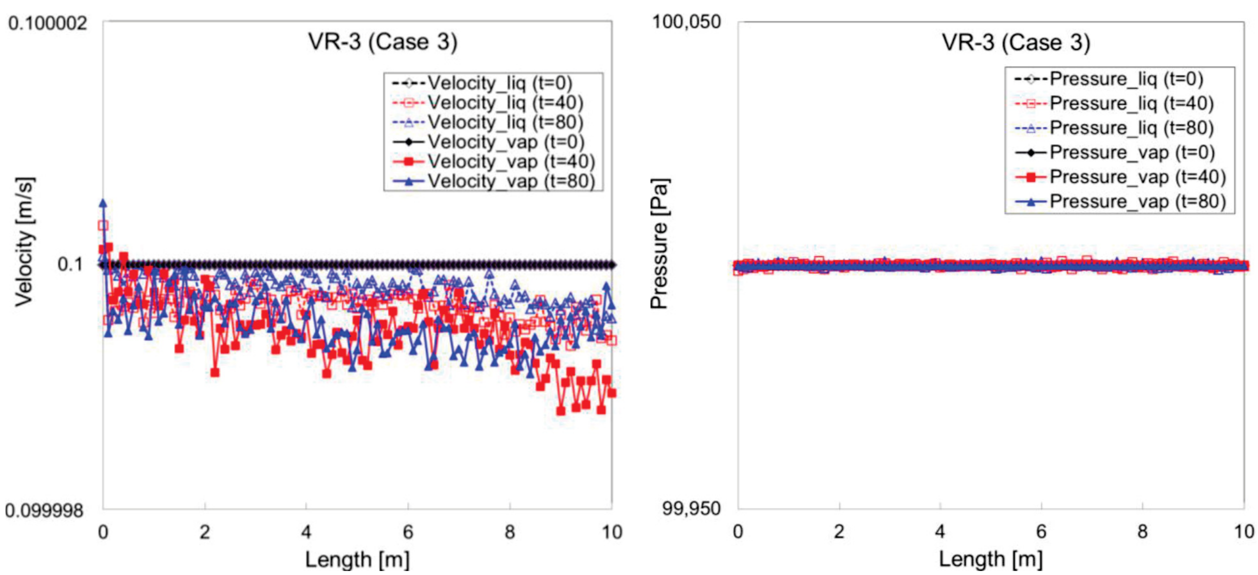


Figure 11. Velocity (left side) and pressure (right side) values along the pipe for Case 3

2.2 Validation Tests

2.2.1 Water-faucet problem

Problem description

This is a demonstration problem used for the validation of RELAP-7 (7-equation model) in which water falls through a vertical pipe under the influence of gravity. Note that the same test problem is included in the code assessment matrix of RELAP5-3D [3]. This test problem can have an exact solution if several assumptions are taken, *i.e.*, negligible pressure gradient, incompressible fluid flow, and steady state ($u_{liq} = \sqrt{2gz + u_0^2}$, where u_0 is initial velocity and z is distance from the inlet.). Due to the effect of gravity, the liquid velocity is expected to increase with distance from the inlet (see Figure 12). On the other hand, the liquid fraction should decrease as the liquid velocity increases because of continuity considerations (*i.e.*, $\rho_1 u_1 = \rho_2 u_2$). The initial and boundary conditions used for this test problem are summarized in Figure 12.

Test result and discussion

The inlet liquid velocity is given as 10 [m/s] in downward direction during the simulation (Figure 12). Other test conditions are given as those used in RELAP5-3D code assessment manual [3]. The result shown in Figure 13 indicates that the steady state solution for the liquid velocity calculated by RELAP-7 (at t=75 [sec]) is very different from the theoretical solution (i.e., the liquid velocity in Figure 13 is decelerated as the water falls through the vertical pipe instead of being accelerated). Also, the effect of gravity was found not to be represented correctly for this problem. Specifically, the solution of this problem was not influenced by the change in the gravity direction although the solution (or liquid flow behavior) is supposed to be dominated by such change.

As for the test result shown in Figure 13 (and other cases were questions in the results occurred), discussion was made with RELAP-7 code developers, some of which are described as follows: First, it appears as if the boundary conditions used by RELAP-7 in this demonstration case are not correct with the current version of RELAP-7 (as of mid-2016). For this problem, 'Inlet' [pipe(in)] and 'Outlet' [pipe(out)] type boundary conditions are used at the inlet and outlet of the vertical pipe, respectively. And 'reversible' flow is allowed at the outlet (see Figure 12). However, the current 7-equation model implemented in RELAP-7 is not ready for the mixed boundary condition where each phase moves in opposite direction at the boundary although the 'reversible flow' is employed as outlet boundary for this "Water-Faucet" problem. Lastly, we plan to implement additional verification cases to check other possible issues (*e.g.*, gravity term) and to verify solution independence to coordinate transformation.

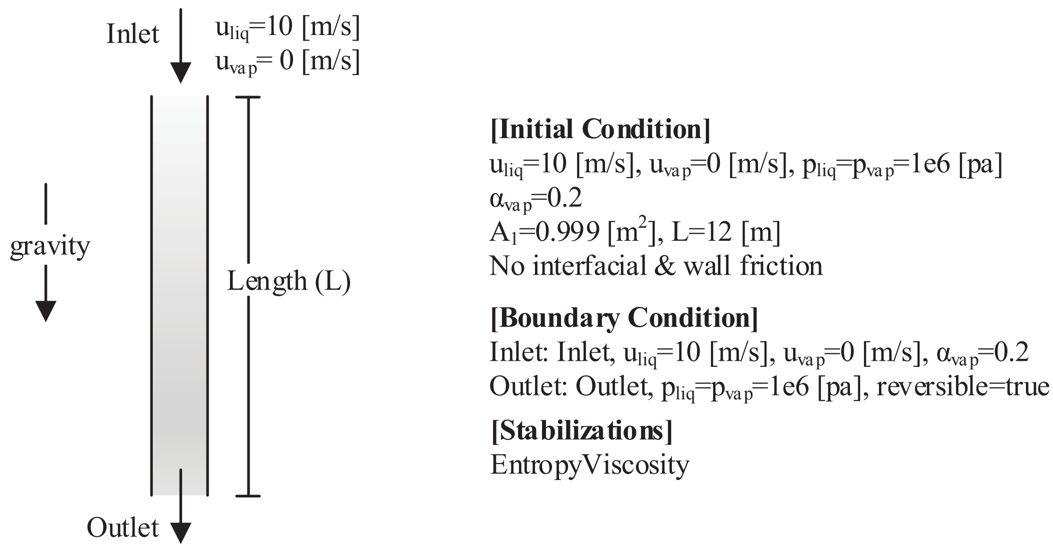


Figure 12. Test conditions for the water-faucet problem

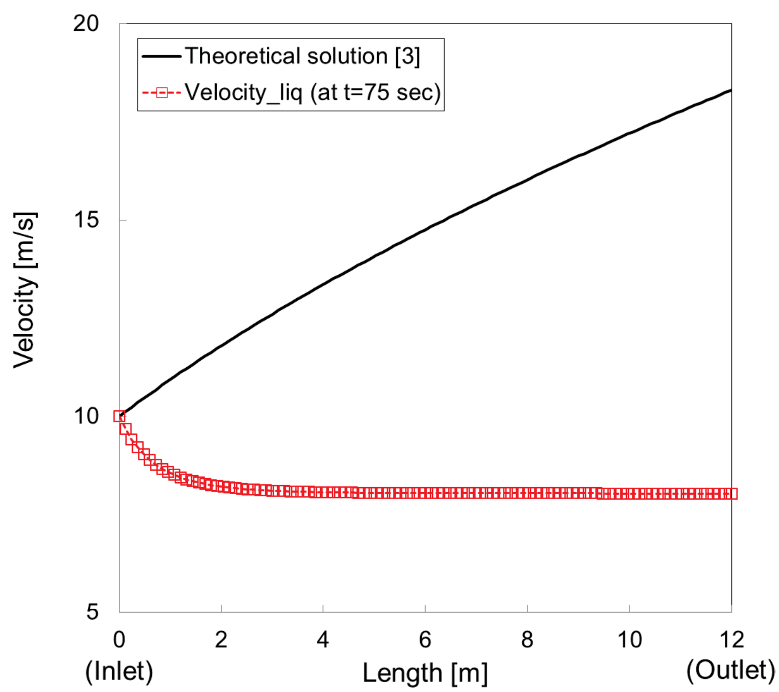


Figure 13. Liquid velocity calculated by RELAP-7 for the water-faucet problem

2.2.2 Phase separation (or sedimentation) problem

Problem description

This example represents a validation test problem to investigate the gravity-induced phase separation and associated counter-current two-phase flow behavior (see Figure 14). No heat transfer is considered (*i.e.*, isothermal). As initial condition (at t=0), the homogeneous two-phase mixture (α_{vap}= α_{liq}=0.5) is filled within a vertical pipe of 10 meter length. Once the simulation starts, the two different phases (*i.e.*, liquid and gas) are expected to be gradually separate with time due to gravity as shown in Figure 14. The specific challenge of this problem is whether or not RELAP-7 code can predict the two steep void waves travelling simultaneously from the top and bottom ends to the middle section of the vertical pipe. In other words, the two void waves (α_{liq}, α_{vap}) are supposed to move simultaneously into the pipe with (nearly) discontinuous changes of void fraction (see Figure 15).

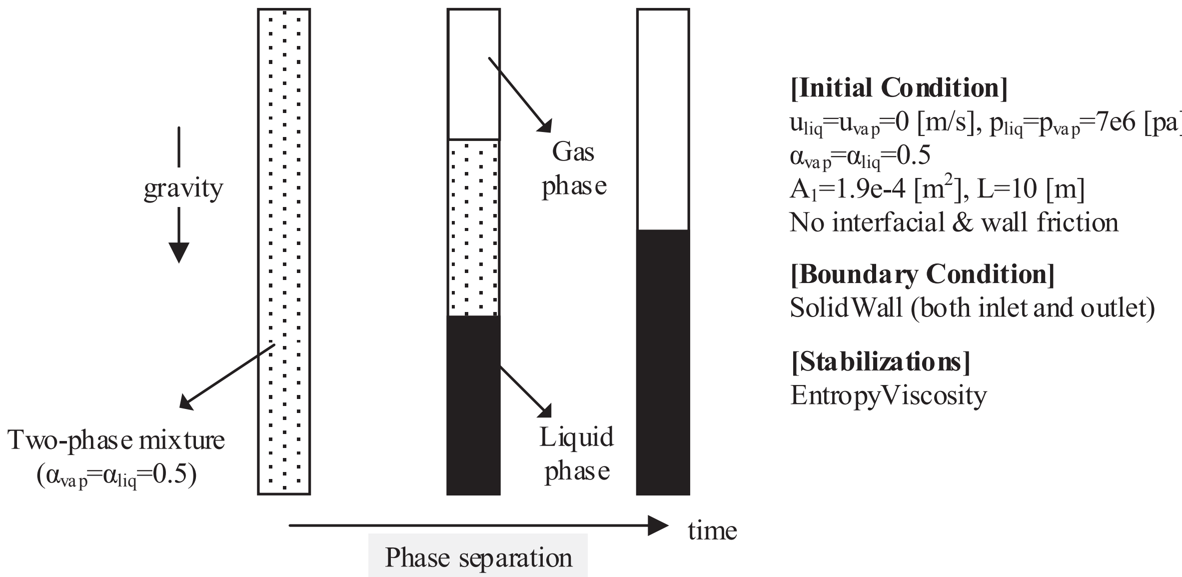


Figure 14. Test conditions for the phase-separation problem

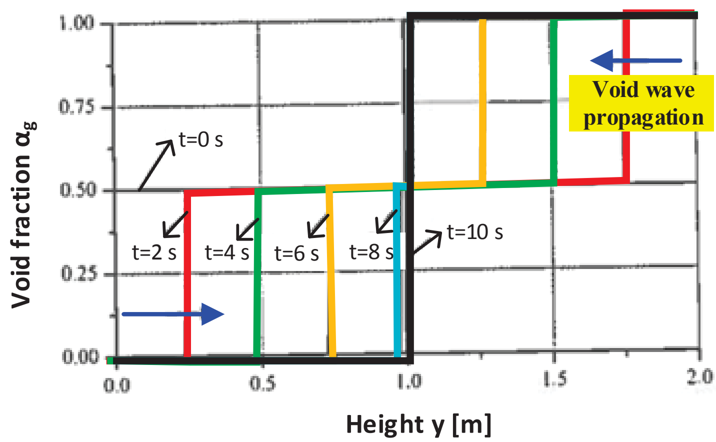


Figure 15. Example of void wave propagation within a vertical pipe for the phase separation problem [4]

Test result and discussion

Figure 16 shows the void fraction development calculated by RELAP-7 for the phase separation problem (Figure 14). The void wave (α_{vap}) propagation into the middle section of the vertical pipe from the both ends is clearly seen in Figure 16. It is noted, however, the result shows the small fluctuations of void fraction around α_{vap} =0.5 at t=20 and 40 [sec] before the equilibrium is reached at the end. These fluctuations are not usually observed in the validation test of the same problem with six-equation based two fluid model [4, 5], implying that more tests are required to better understand this behavior.

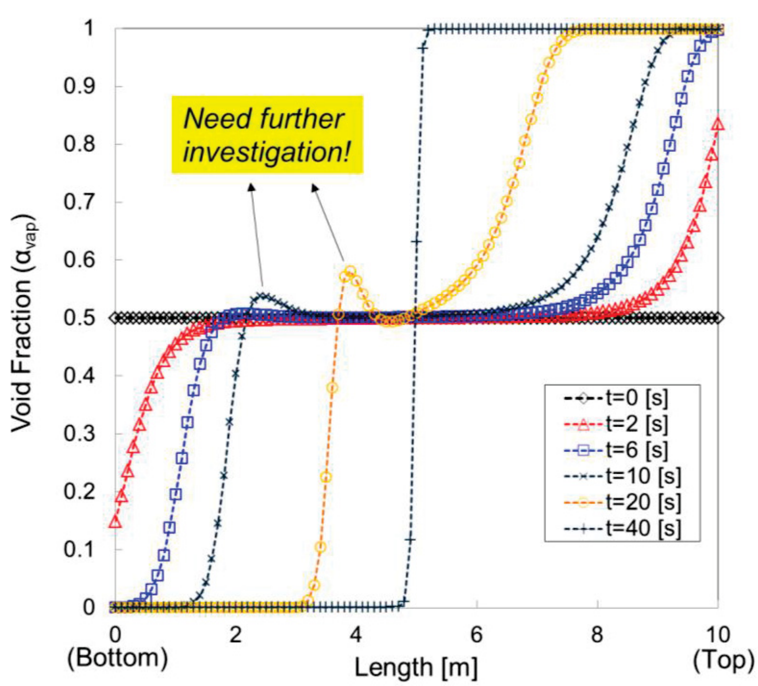


Figure 16. Void fraction development within the vertical pipe (calculated by RELAP-7)

2.2.3 Solution independence test to coordinate transformation

In section 2.2.1, an issue associated with gravity term was considered as one of the problems that kept the test from successfully running. This finding is based the observation that the numerical solution was barely influenced by the change in the gravity direction despite the fact that the solution should be significantly affected by those changes from the physical viewpoint. Accordingly, in an effort to verify whether or not the gravity term is implemented correctly in RELAP-7 (7-equation model), a solution independence test to coordinate transformation was conducted. Specifically, for the test problem described in section 2.2.2 (*i.e.*, phase separation problem), the numerical solutions should depend on the gravitational direction (*i.e.*, x-, y-, or z-direction). To confirm that this dependence was working, we ran the section 2.2.2 case again where we varied the direction of gravity and compared the results. These additional test results showed that the solution shown in Figure 16 was always obtained (influenced, of course, in the direction of gravity) regardless of the changes given to the gravity term. This result gave us confidence that the numerical solution was correctly accounting for the direction of gravity during the coordinate transformation. Note that to change the "gravity direction," we modified the corridinates inside the RELAP-7 input file that describes the demonstration case. This test outcome implies that the gravity term works in the RELAP-7 7-equation model and does not appear to be the reason causing the issue discussed in section 2.2.1. Therefore, the issue may be placed on the other considerations such as boundary condition treatment to make the test problem be correctly solved with RELAP-7.

3. SUMMARY AND CONCLUSIONS

The RELAP-7 simulation results are discussed in this document with verification and validation test problems adopted from the list of "RELAP-7 *code V&V RTM*." A total of five test problems have been described in this document to illustrate the types of tests used to perform the V&V process for the present RELAP-7 code assessment.

The first two verification tests performed at hydrostatic condition (section 2.1.1 and section 2.1.2) showed that without gravity the flow velocities of both phases remained zero and no pressure fluctuation was found. That is, the hydrostatic equilibrium was well maintained during the simulation. On the other hand, the significant fluctuation of vapor velocity was found once gravity was taken into account for the simulation. The other verification test to investigate the void fraction advection (section 2.1.3) revealed that the initial void fraction profile is significantly deformed while it is advected due to the numerical dissipation and dispersion. In particular, the code stopped when the void fraction (α_{vap}) went below zero as a result of the numerical dispersion (i.e., undershooting). Also, the pressure and velocity of the vapor phase significantly fluctuated when such undershooting of α_{vap} occurred before the code stopped.

For validation tests, the RELAP-7 simulation for the water-faucet test problem (section 2.2.1) showed different results from the theoretical solution. Additional test on mixed boundary condition is required. On the other hand, the phase separation test problem (section 2.2.2) gave us physically reasonable result. However, the fluctuating behavior of void fraction during the separation of two different phases still needs to be further studied.

4. REFERENCES

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