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A Comparison of Code Developmental Assessment Results of 1D Module of MARS 2.1 and RELAP5/MOD3.3

S.W. Bae, Y. J. Lee , B. D. Chung

Korea Atomic Energy Research Institute
Dukjin 150, Yuseong, 305-600 Daejeon, Korea
e-mail : yjlee1@kaeri.re.kr

Abstract

The one-dimensional module of MARS 2.1 thermal hydraulics analysis code has been validated against the RELAP5/MOD3.3 by comparing the results of the two codes. Nine phenomenological and conceptual simulation problems of the RELAP5 Code Developmental Assessment Problem were selected for the validation calculations using identical inputs.

The results demonstrate that the one–dimensional module of the MARS 2.1 code and the RELAP5/MOD3.3 code give essentially the same results. This is expected since the basic formulations, numerical schemes and most models and correlations of the one-dimensional module of the MARS code are identical to those of RELAP5 code. The results imply that the code validity of the RELAP5 code can be applied to the MARS one-dimensional module.

1. Introduction

MARS computer code is a best estimate thermal hydraulics analysis code developed for the systems analysis of light water reactor transients.[1,2,3] The one-dimensional module of the MARS code is a re-structured version of the RELAP5 code.[4] And the basic field equations, constitutive relations and most of the thermal hydraulic models of the one-dimensional module of MARS are identical to those of RELAP5. The MARS is distinguished from RELAP in that MARS is capable of multi-dimensional modeling and analysis capabilities. The most up-to-date RELAP5 version is the MOD 3.3 released in March 2002. The added capability in RELAP5/MOD3.3 includes new modeling improvements, and new user convenience features. A detailed description of the MOD3.3 capabilities can be found in Volumes I and II of the RELAP5/MOD3.3 code manual. The one-dimensional module of MARS has been upgraded to RELAP5/ MOD3.3 level to generate MARS 2.1.

The purpose of this study is to demonstrate, by way of comparison of results, that the one-dimensional module of MARS 2.1 and RELAP5/MOD3.3 give basically the same results and that they are essentially the same codes. For the purpose of comparison, the simulations used in the developmental assessment of RELAP5/MOD3.3 have been selected for analyses.[5] The objective of the developmental assessment is to determine the qualitative and quantitative accuracy of the code for problems that are consistent with the intended application of the code.

2. Assessments

A total of nine cases of assessment were carried out. Table 1 shows the list of the code assessment problems carried out in the current effort. Table 1 also shows the assessment objectives of each of the problem. The phenomenological/conceptual problems are selected to demonstrate that the two codes are in qualitative agreement with the physics of the problem and to each other. In cases where analytical solutions exist, the accuracy of the code can be judged quantitatively. Qualitative agreement between the codes is the first criteria that must be satisfied and the code results can then be quantitatively compared.

Table 1. List of Assessment Problems

Problem	Assessment Objectives	Problem	Assessment Objectives
Nine-Volume Water over Steam	- Gravitational head effect - Two fluid kinematics	Nitrogen-Water Manometer Problem	- Noncondensible state - Momentum formulation - Level tracking model - Flow oscillation
Branch Re-entrant Tee	- Tee model using branch component	Cross Tank Problem	- Crossflow feature - Non-physical recirculating flow
Crossflow Tee	- Tee model using crossflow feature		
Horizontal Stratified Counter-Current Flow	- Counter-current flow model	Pryor's Pipe Problem	- Water packing
Workshop Problem 2	- Hypothetical PWR - System modelling - Control system - Steady-state option	Workshop Problem 3	- Hypothetical PWR - System modelling - Control system - Restart

2.1 Nine-Volume Water over Steam Problem

A vertical pipe was modeled using nine volumes and eight junctions. The upper three volumes were initially filled with saturated water at a pressure of 413 kPa, and the bottom six volumes were filled with saturated steam at a pressure of 413 kPa. Then the top liquid was allowed to fall and displace the vapor in the bottom three volumes. Counter current flow develops which restricts the rate of fall of the liquid, both due to frictional effects and due to the pressure gradient associated with the upward vapor flow. Figure 1 shows the RELAP5/MOD3 nodalization diagram. The calculated local void fraction histories for volumes 3, 5 and 7 are shown in Figure 2 through 4. The results show that gravitational effect and kinematic models for phase continuity of MARS 2.1 are identical to those of RELAP5/MOD3.3, and these models provide a qualitatively correct result.

2.2 Nitrogen-Water Manometer Problem

A 20-volume nitrogen-water manometer, as shown in Figure 5, was set up to check the non-condensable state calculation, the code momentum formulation for periodic flow, and the level tracking model. The manometer problem has an analytical solution and the calculated period of the oscillation can be checked. The manometer was modeled using a pipe component. The first 10 volumes were oriented vertically downward and the last 10 volumes were oriented vertically upward. A time dependent volume and single junction was connected to both the pipe inlet and outlet. The bottom five volumes on both sides were filled initially with water at 100.11 kPa and 323 K. The remaining volumes were initialized with dry nitrogen at the same pressure and temperature. The wall friction flag was turn off for both codes and the mixture level tracking model was turned on for RELAP5. In order to make the MARS calculation run, the mixture level tracking model had to be deactivated. To initiate the oscillation, an initial velocity of -1.0 m/s was placed at each junction.

A comparison of the liquid velocity at the bottom of the manometer is shown in **Figure 6**. Analytically, the amplitude of the liquid velocity should remain constant but MARS over-predicts initial velocity and then predicts decaying amplitude whereas the RELAP 5 correctly calculates constant amplitude. **Figure 7** shows the liquid level comparison. Again, MARS over-predicts initial velocity and then predicts decaying amplitude. The calculated period of oscillation for both MARS and MOD3.3 is shown to be about 4.5 seconds which agrees well with the theoretical period of the oscillation of 4.486 seconds.

The results indicate that qualitatively, MARS and MOD3.3 agree well with the theoretical period of oscillation. Thus the ratio of gravitational force to inertia calculated by the code is correct. The results also show that the mixture level tracking model of RELAP5 allowed almost zero numerical damping or decay in the maximum velocity and level. Thus, similar level tracking model is recommended for implementation in MARS.

2.3 Branch Re-entrant and Crossflow Tee problem

The branch reentrant tee problem is a conceptual problem to test the ability of the branch component to accurately model a tee for single- and two-phase inflows. The branch reentrant tee model is constructed of two equal length, equal area side by side horizontal pipes connected to the outlet side of a horizontally oriented branch component that represents the tee. A time dependent volume is connected to the upstream side of each of the pipes by a single junction. A horizontally oriented single volume is also connected to the outlet side of the branch component. A time dependent volume is then connected to the downstream side of the single volume. The nodalization diagram for this case is shown in Figure 8.

The fluid conditions set in the supply sources and all components up to the sink volume are single-phase, saturated water, at 2.63962 MPa and 500 K. The fluid conditions set in the sink volume are single-phase saturated water at 2.5 MPa and 497.09 K. Fluid flows from the pipes through the tee and into the sink volume. The problem was run to 20 seconds with two-phase conditions developing in the pipes and branches due to depressurization caused by the lower pressure in the sink volume.

The results of the MARS and MOD3.3 calculations are shown in Table 2. The values shown (taken at 20 seconds) are the mass flow rates in the two pipes upstream of the branch component and the junction to the sink volume. Symmetrical flow in the two pipes upstream of the modeled Tee component was calculated by both MARS and MOD3.3. Thus it is demonstrated that the unphysical characteristics of oscillatory and unsymmetrical flow that have been encountered with earlier versions of the RELAP5 code do not occur in either the MARS or MOD3.3. The total mass flows calculated by MARS and MOD3.3 agree exactly and the calculated discharge mass flow rates of MARS and MOD3.3 agree with the respective combined pipe mass flow rates.

The cross-flow tee problem is a conceptual problem that was developed to test how the new cross-flow junction feature of RELAP5/MOD2 could be used to model a variant of the branch re-entrant tee problem. It was selected to ascertain whether non-oscillatory and symmetrical flows result occurs in MARS or RELAP.

The model nodalization for this problem is similar to the model presented in the previous section except that the outflow is modeled using a vertical single. The nodalization diagram is shown in Figure 9. The tee volume was square and oriented from left to right. The perpendicular junctions were made crossflow junctions. The fluid conditions were the same as the branch-tee model presented previously. The problem was run to 20 seconds with two-phase conditions developing in the pipes and branches.

The results are summarized in Table 3. The values shown (taken at 20 seconds) are the mass flow rates in the two pipes upstream of the tee volume and the junction to the sink volume. As in the previous case, there was symmetrical flow calculated in the two pipes upstream of the tee volume and the calculated mass flow rate downstream of the tee volume was the combination of the two pipe flows. The calculated discharge mass flow rate for MOD3.3 agrees well with the combined mass flow rates of the two upstream pipes. MARS calculated results show better agreement between the calculated discharge and the combined pipe mass flow rates as compared with those of MOD3.3 results. This is probably a result of the mass error calculated between MARS and MOD3.3. The mass flow rates obtained in the two calculations are very close.

This problem demonstrates that crossflow junctions can be used to model the behavior of a tee without encountering unphysical behavior and minimal differences exist in results obtained using MARS and MOD3.3.

2.4 Cross Tank Problem

This problem is designed to test the flow anomalies that may appear as re-circulating two-phase or single-phase flows when the cross-flow junctions are used to model multidimensional effects. The cross tank model consists of two vertically oriented pipe components equally divided into 19 volumes and is shown in Figure 10. A total of 19 cross-flow junctions connect the two pipe components (one for each volume). The bottom 15 volumes in each pipe component were initialized with water at 0.1014 MPa and 305 K. Volume 16 in each pipe component contained a mixture of air and water in equilibrium condition with a static quality of 0.5 and a pressure and temperature the same as the liquid. The remaining three top volumes of each pipe component are initialized with air at the same pressure and temperature as the liquid, with a static quality of 1.0 in equilibrium conditions. The problem was run using null flow conditions ($v_g = v_f = 0.0$).

The calculated mass flow rates just below and above the liquid level in each of the two pipe components and the corresponding connecting cross-flow junctions are shown in Figure 11 and 12. All of the cross-flow junction mass flow rates remained near zero for the MARS and MOD3.3 cases. The spontaneous recirculation flows which were observed in the MOD3.2 calculations are absent in both the MARS and the MOD3.3 calculated flows which remain near zero.

The results demonstrate that the problem or problems causing the non-physical recirculation flows calculated by MOD3.2 have been corrected in MARS and MOD3.3.

2.5 Horizontal Stratified Counter-Current Flow Problem

The horizontally stratified countercurrent flow problem is a conceptual problem involving a horizontal pipe closed at both ends with a linearly graduated liquid level. Because of the hydrostatic pressure difference caused by stratification, the liquid flows from the higher-level side to the lower-level side and the vapor flows in the opposite direction from the liquid and a countercurrent flow develops. This problem was designed to check the countercurrent flow model and to verify that the speed of propagation for a void wave is qualitatively correct.

Figure 13 shows the RELAP5 nodalization diagram. The pipe was modeled using 20 volumes and 19 junctions (total pipe length 10 m, pipe flow area = 0.19635 m^2). The pipe is initially filled with a linearly distributed, two-phase, saturated, liquid/vapor mixture at a pressure of 10 MPa; and the quality varies from 0.083 to 0.067 which corresponds to an average void fraction of approximately 0.5.

The calculated history of the liquid and vapor junction velocities at mid-section are shown in Figure 14 and 15**.** The liquid flows from right to left and the vapor flows from left to right and the void profile propagates as a wave. As observed, there is no difference between MARS and MOD3.3. Thus the code modifications implemented between these two code versions does not affect the results of this problem. The speed of propagation from the calculated results is 0.74 m/s while the theoretical value for a stratified wave in frictionless flow is 2.8 m/s. The lower speed of propagation determined from the calculations is qualitatively in the right direction as a result of the interphase drag and virtual mass models (which are inherent in the codes). These results show qualitatively that the horizontal stratified flow model in MARS and MOD3.3 is functioning properly.

2.6 Pryor's Pipe Problem

The Pryor's Pipe Problem was developed to check the water packing problem that can occur in the finite difference scheme. The problem consists of a horizontal pipe section, a water injection system, and a constant pressure exit system. The nodalization diagram is shown in Figure 16. Initially, the pipe was filled with slightly superheated vapor, at a pressure of 0.4 MPa and a temperature of 418.2 K. Subcooled liquid at a pressure of 0.4 MPa and a temperature of 353 K was injected into the inlet side of the pipe and the opposite end is open to a time dependent volume at a pressure 0.4 MPa. The model consists of 20 volumes and 19 junctions for the pipe section, a time-dependent volume and junction for the water injection source, and a time-dependent volume and single junction for the discharge system.

Local void fraction and pressure in volume 2 are shown in Figure 17 and 18. The calculations were run with the water packer turned on. The MARS and MOD3.3 calculations (with water packer on) do not show these pressure spikes as the volumes fill with water. It is also noted that the code calculated responses for the two versions are essentially the same.

2.7 Workshop Problem 2 (Hypothetical PWR)

This problem was named Workshop Problem 2 as it was used as the second demonstration problem during the RELAP5/MOD1 workshop held in April 1982. It was set up to simulate one loop of a two-loop pressurized water reactor (PWR) and to assess the system modeling capability of the RELAP5 computer code, including the control features, for steady-state operation. The system consists of a primary system loop and a steam generator secondary recirculation loop. The primary loop contains a reactor vessel, including an electrically heated reactor core, a pressurizer, a hot leg, a once-through steam generator, a coolant pump and a cold leg. The steam generator secondary loop consists of the heat exchanger tube region, separator, and downcomer. Feedwater is supplied from a time dependent junction and volume. Steam is discharged from the secondary loop through a control valve connected to a time dependent volume.

The nodalization diagram for the system is shown in Figure 19**.** The model consists of four time-dependent volumes, twenty-six regular volumes, twenty-one junctions, one pump, two valves, and six heat structures. The built-in, homologous curves for the Westinghouse pump were used to model the pump behavior. The primary system pressure is initially set at $1.5x10^7$ Pa with an average system temperature of 550 K and a primary system flow at 131 kg/s. The core power is set at 50 MW. The secondary side pressure is set at $2.0x10^6$ Pa with feedwater flow and temperature set at 26.1 kg/s and 478 K, respectively.

The calculations were performed with the steady-state option. Figure 20 to 23 show the MARS and MOD3.3 calculated volume pressure in the pressurizer, core outlet, and steam dome of the steam generator secondary side, respectively. The calculated pressure responses for both codes were similar in both the primary side and the secondary side.

The steam generator secondary liquid level comparison is shown in Figure 22. The calculated liquid levels for the two codes are almost identical. Figure 23 Figure show the mass flow rate in the hot leg to the pressurizer. The MARS and MOD3.3 results are almost identical, which implies that the heat transfer from the primary side to the secondary side is similar in the two codes.

2.8 Workshop Problem 3 (Hypothetical PWR)

Workshop Problem 3 simulates a modified station blackout transient for the system described in Workshop Problem 2. As with Workshop Problem 2, this is a hypothetical problem which was originally used to demonstrate the transient simulation capability of RELAP5 when applied to a system problem. The model of Workshop Problem 2 was used for the transient analysis except that the pressurizer time-dependent volume (Component 132) was replaced by a vertical, two-volume pipe (Component 132), a pressurizer relief valve (Component 133 - trip valve), and a time-dependent volume (Component 134) as shown by the bracket and arrow in Figure 19. In the model, the steady-state conditions calculated from Workshop Problem 2 were used as initial conditions; and the transient sequence used the following boundary conditions: 1) relief valve opens when the pressurizer pressure exceeds 18.0 MPa, and 2) reactor shutdown occurs after 5 seconds continuous actuation of the pressurizer relief valve.

Figure 24 shows the volume pressure in the pressurizer. The primary pressures calculated by MARS and MOD 3.3 are very similar out to about 20 seconds. The primary loop mass flow rate calculated by MOD3.3 was higher as shown in Figure 25. The primary loop mass flow rate and the mass flow rate out of the pressurizer through the relief valve calculated by MARS are almost identical those of MOD3.3 as shown in Figure 26. At about 35 seconds the calculated pressures of MARS and MOD3.3 dropped below the pressurizer relief valve closing setpoint and the flow out the valve stopped. After about 70 seconds the MARS and MOD3.3 calculated primary loop flow was steady at about 10 kg/s (natural circulation) with a liquid full system.

Figure 27 shows the secondary loop mass flow in the steam generator. At the initiation of the transient, the steam line control valve was closed, along with the feedwater flow, and the secondary side pressure relief valve opened. The pressure temporarily decreased until the energy being transferred to the secondary side from the primary side exceeded the energy being removed through the relief valve and the pressure began to increase as shown in Figure 28. As the energy being removed from the primary side declined, the energy removal rate through the secondary side relief valve began to dominate and the pressure response turned over. The pressure decreased until the relief valve closing pressure was reached and the valve closed. The pressure then increased to the relief valve open setpoint, the valve opened and the pressure declined. The valve cycled in this manner through the remainder of the transient. The results of MARS and RELAP are quite close and considering that the codes are highly non-linear and that there are numerous cut-off and decision values, the results of the two codes are quite similar.

3. Conclusion

To demonstrate that the one-dimensional module of the MARS 2.1 computer code and the RELAP5/MOD3.3 computer code give essentially the same results, simulations of 9 phenomenological or conceptual problems have been performed and the results were compared.

These simulations were performed to demonstrate that the two codes are in qualitative agreement with the physics of the problem and to each other. Except in the case of Nitrogen-Water Manometer Problem, the results of all other simulations show that the MARS and RELAP5 code give physically correct results and the results are indistingushably similar to each others. For the Nitrogen-Water Manometer problem, MARS code gave unphysical results whereas the RELAP5/MOD3.3 gave 'correct' results. The difference is traced to the lack of level-tracking model in MARS code.

The one-dimensional module of the MARS code has been demonstrated, by means of comparing results of code developmental assessment problems, to have essentially the same capability as the RELAP5 code. For all practical purposes, the basic physics on which the one-dimensional module of MARS code and the RELAP5 code are based can be seen to be the same. This is expected as most of the basic field equations, program layout, constitutive equations and thermal hydraulic models of the two codes are identical.

References

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[2] Won-Jae Lee et al, 2002, Development of Realistic Thermal-Hydraulic System Analysis Code, KAERI/RR-2235/2001

[3] Won-Jae Lee et al, 1998, Development of a Multi-Dimensional Realistic Thermal-Hydraulic System Analysis Code, MARS 1.3 and Its Verification, KAERI, KAERI/TR-1108/98

[4] The Thermal Hydraulics Group, " RELAP5/MOD3 Code Manual Volume I : Code Structure, System Models, and Solution Methods", RELAP5/MOD3.2.2 Beta, NUREG/CR-5535,Scientech, Inc., Idaho Falls, Idaho, March (1998)

[5] V.H. Ransom et al., RELAP5/MOD2 Code Manual, Volume 3 : Developmental Assessment Problems, EGG-TFM-7952, December 1987.

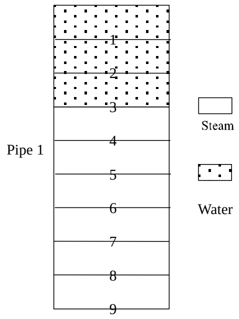

Figure 1 Nodalization for Nine-Volume Water over Steam Problem

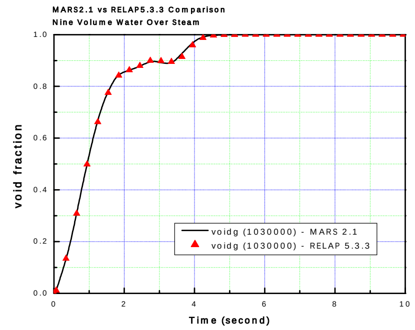

Figure 2 Void history for volume 3

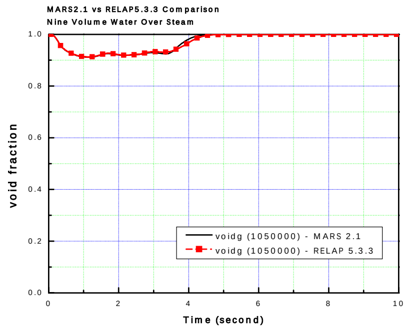

Figure 3 Void history for volume 5

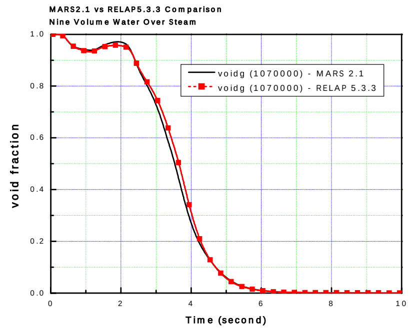

Figure 4 Void history for volume 7

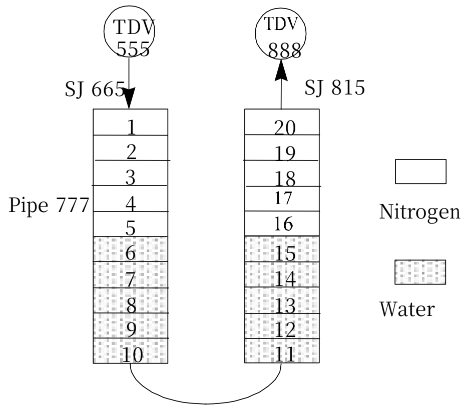

Figure 5 Nodalization for Nitrogen-Water Manometer Problem

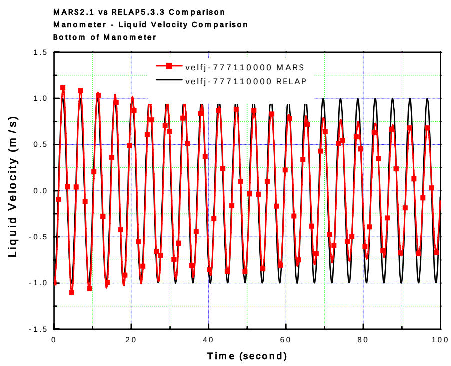

Figure 6 Liquid Velocity at the Bottom of the Manometer (junction 777110000)

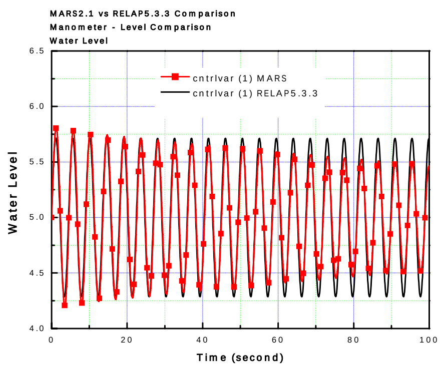

Figure 7 Calculated Water Level Comparison for the Manometer Problem

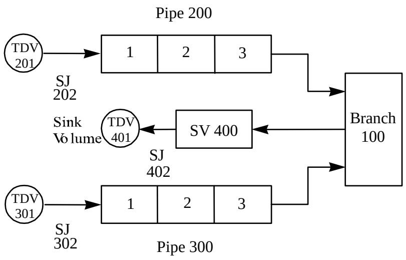

Figure 8 Nodalization for Branch Tee Problem

Table 2. Results for the Branch Tee Problem

Variable	MARS	MOD3.3
Mass flow rate in Pipe Component 200	897.88 (kg/s)	897.88 (kg/s)
Mass flow rate in Pipe Component 300	897.88 (kg/s)	897.88 (kg/s)
Summation of mass flow rate	1795.76 (kg/s)	1795.76 (kg/s)
Mass flow rate in Single Junction 402	1795.8 (kg/s)	1795.8 (kg/s)
Mass error	-0.574 (kg)	-0.575 (kg)

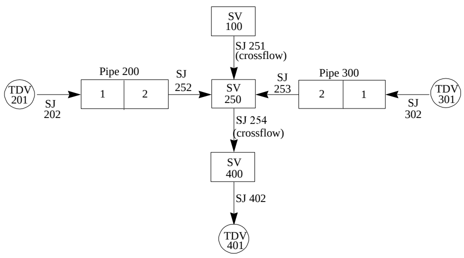

Figure 9 Nodalization for Crossflow Tee Problem

Table 3. Results for the Crossflow Tee Problem

Variable	MARS	MOD3.3
Mass flow rate in Pipe Component 200	656.05 (kg/s)	656.0 (kg/s)
Mass flow rate in Pipe Component 300	656.05 (kg/s)	656.0 (kg/s)
Summation of mass flow rate	1312.1 (kg/s)	1312.0 (kg/s)
Mass flow rate in Single Junction 402	1312.7 (kg/s)	1312.8 (kg/s)
Mass error	-0.14761 (kg)	-0.15201 (kg)

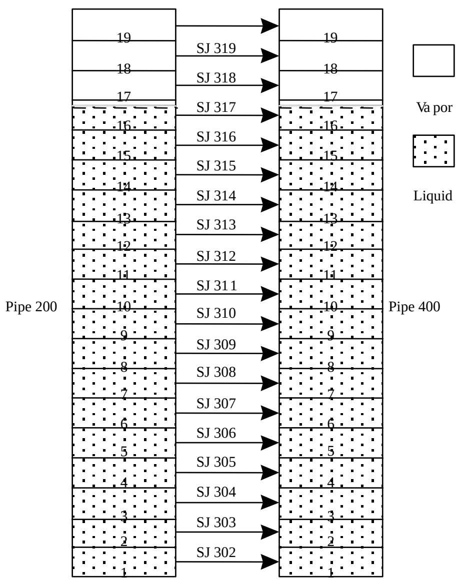

Figure 10 Nodalization for Cross Tank Problem

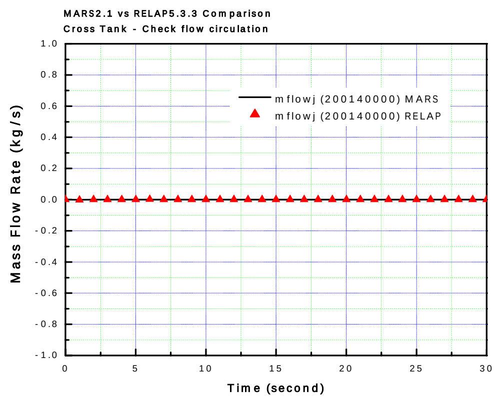

Figure 11 Crossflow in Liquid Region

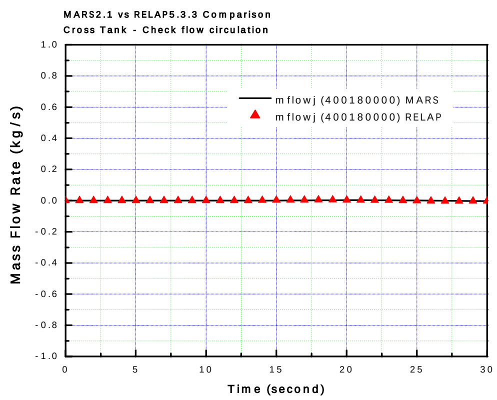

Figure 12 Crossflow in Gas Region

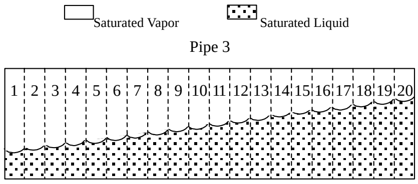

Figure 13 Nodalization for Counter-current Flow Model Problem

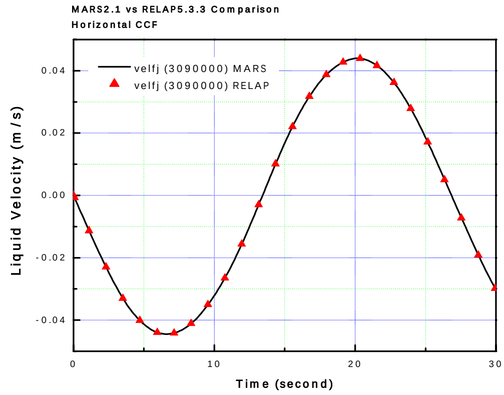

Figure 14 Liquid Velocity at Mid-section

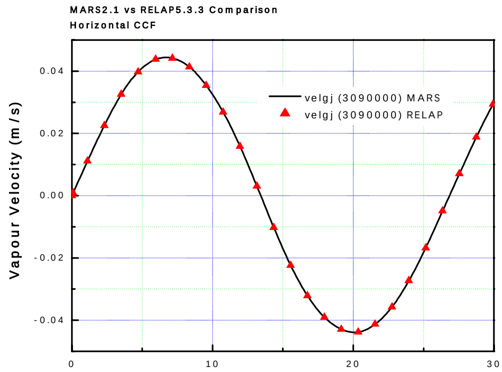

Figure 15 Vapour Velocity at Mid-section

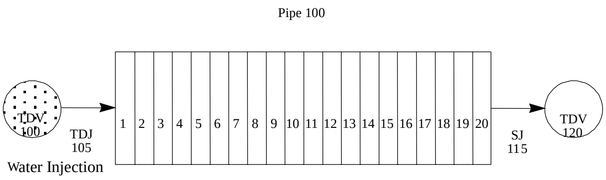

Figure 16 Nodalization for Pryor's Pipe Problem

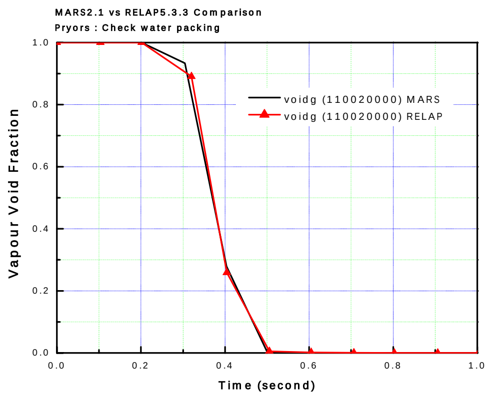

Figure 17 Void at volume 2

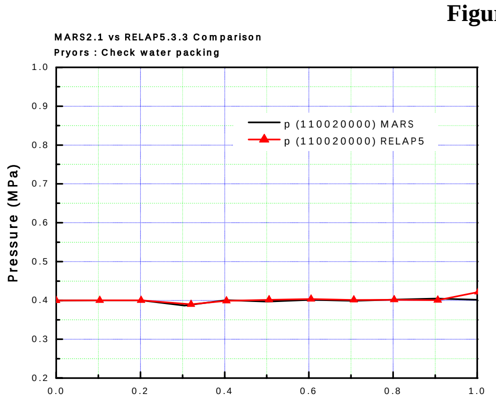

Figure 18 Pressure at volume 2

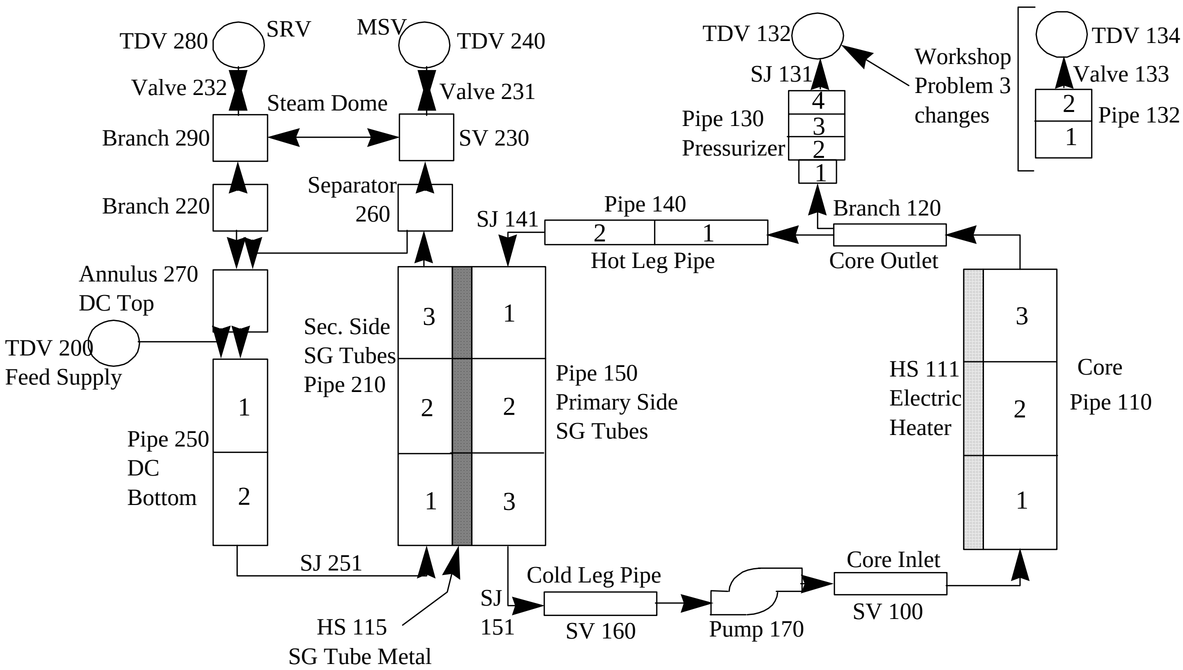

Figure 19 Nodalization for Workshop Problem 2

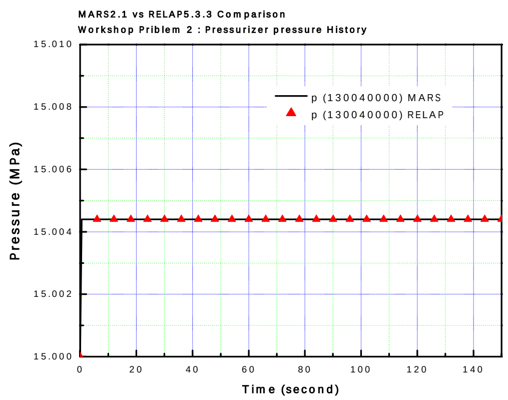

Figure 20 PZR Pressure

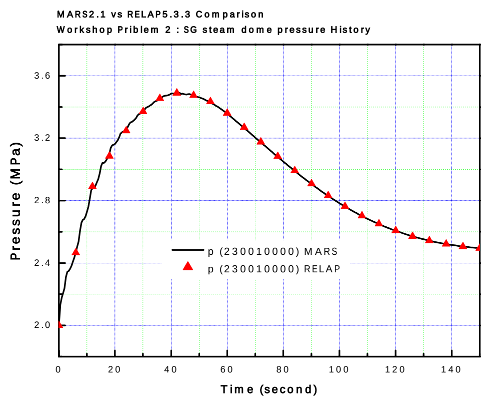

Figure 21 SG Pressure

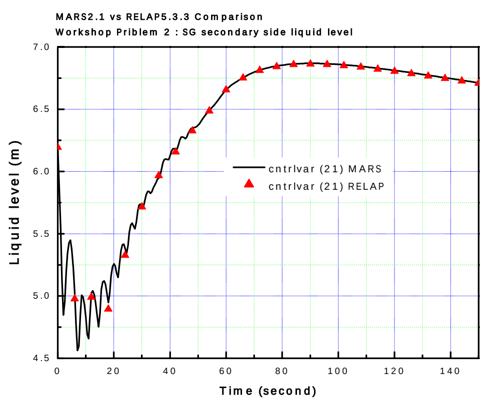

Figure 22 SG Level

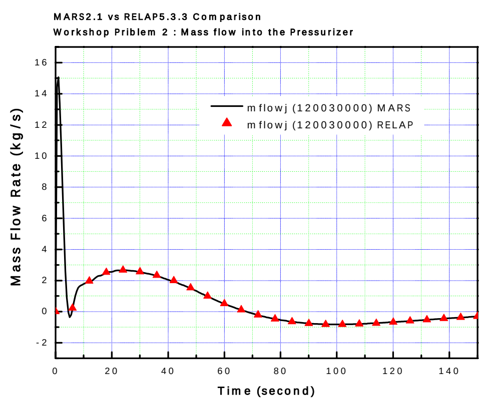

Figure 23 Primary Loop Massflow

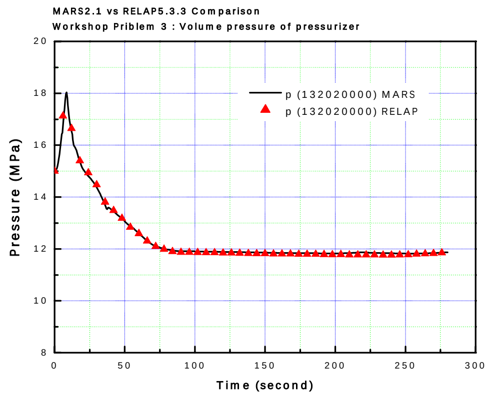

Figure 24 PZR Pressure

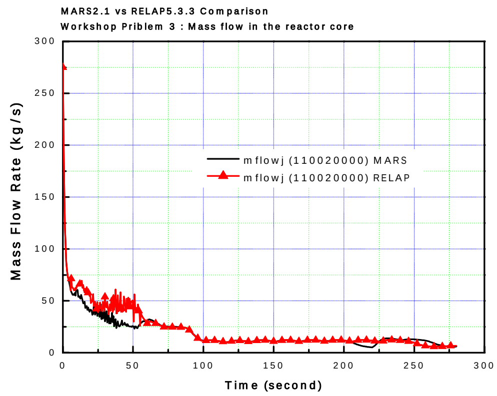

Figure 25 Mass Flow in Reactor Core

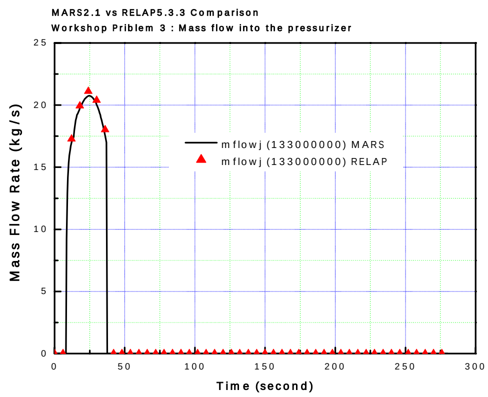

Figure 26 Discharge from PZR through Relief Valve

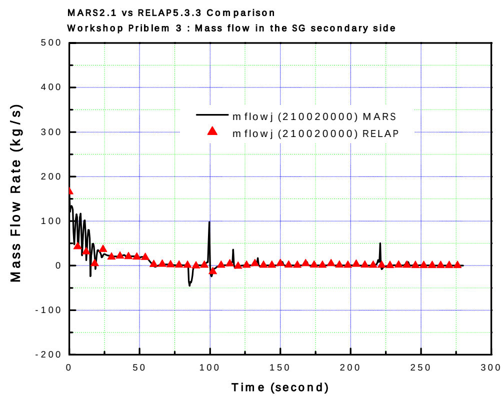

Figure 27 Mass flow in SG Secondary (Riser)

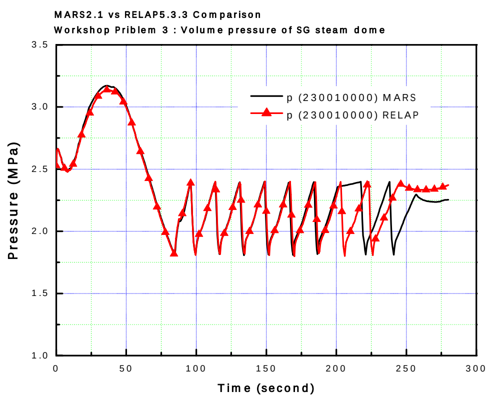

Figure 28 SG Steam Dome Pressure