ON THE DEFINITION OF A MINIMUM SET OF REQUIREMENTS TO ASSESS THE ADEQUACY OF THE RELAP5-3D MULTIDIMENSIONAL FLOW CAPABILITY WITH SELECTED CANONICAL PROBLEMS

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ABSTRACT

A key step in the process is the selection of the computational device (or code) and the development of a robust strategy for the assessment of the code capabilities for its intended purpose. RELAP5-3D, an outgrowth of the widespread RELAP5 code, was designed to extend its capabilities in handling complex multidimensional flow. A project was setup to systematically assess these capabilities following a rigorous top-down and bottom-up approach. This paper will focus on developing a minimum set of requirements, or metrics that an assessment suite must include to demonstrate an EM is adequate for its intended purpose. Complex systems are analyzed by breaking them down into a hierarchy of constituents and layers of process complexity. Similarly, RELAP5-3D is assessed in a hierarchical fashion by isolating simple processes first and building complexity along the way. The first stage in the process is to develop simple and fundamental canonical problems which challenge key aspects of the multidimensional flow process while removing other complex processes such as interfacial mass and heat transfer. The goal is first to explore that basic criteria of symmetry, mesh rotation invariance, wave dispersion, hydraulic instabilities, effect of gravity, etc., are predicted consistently with theoretical expectations. This work illustrates this systematic process and some preliminary results from this initial stage of the assessment. The assessment described here was done in the framework of an automated suite which allows for easy reassessment of future code versions and enable future extensions as the assessment suite is expanded to cover more complex features.

KEYWORDS
RELAP5-3D, Testing, Verification, Assessment, System Code, Multi-Dimensional, EMDAP

1. INTRODUCTION

The premises for a robust assessment of system codes used in the nuclear industry are in the design of a systematic, transparent, traceable and scalable verification and validation matrix. The EMDAP formulated in the Regulatory Guide 1.203 [1] provides a reasonable roadmap to achieve this goal. However further steps need to be taken to provide the desired completeness of the exercise.
Aumiller [2] introduces some of these concepts. The characteristics of a complete assessment start with a clear definition of objectives (which features to test, which problems to test) and identification of suitable metrics to reach an objective judgment of the adequacy of the tool under review.

Given the complexity of the problem to be solved, the initial step is a hierarchical system breakdown. Hierarchical system decomposition methods are used to analyze complex systems. A parallel system hierarchical decomposition is performed on the code functions and the phenomena or processes the functions are intended to describe. The typical hierarchical decomposition for the system is presented in Section 1.1.3 of RG 1.203. The hierarchical tree can be further divided in domain synthesis and domain analysis as follows:

- Domain synthesis
    - System
    - Subsystem
    - Modules
    - Constituents
    - Phases
    - Geometry
    - Topology

- Domain analysis
    - Fields
    - Transport processes

The assessment of the tools is then structured following a two-tier review process which starts from a bottom-up assessment followed by a top-down integration of the information. This provides a traceable pattern of knowledge building steps which systematically take the analyst or reviewer to an informed decision on the adequacy of the EM in modeling the target engineering device.

The outcome of the analysis is the identification of areas needing improvements, if any, and the definition of the modeling guidance, which justifies use of the EM for its intended purpose. Starting from the bottom, the first task is to solve the transport of a property within specific fields in a specific domain which geometrically describes the system. What emerges from the hierarchical breakdown is that one of the first steps in any assessment activity is to confirm the adequacy of the chosen numerical model to properly represent the mathematical model tracking the conserved field properties, such as mass, momentum, and/or energy. This is described as "domain analysis" above and part of the verification of the code. This is described here as the "minimum set of requirements" for the verification of the code multidimensional capabilities. Simple problems are designed to explore the basic criteria of symmetry, mesh rotation invariance, wave dispersion, hydraulic instabilities, effect of gravity, etc., are predicted consistently with theoretical expectations.

In subsequent stages of the analysis the adequacy of the model is justified by assessing if the same synthesis can be conducted to satisfaction for different geometrical configurations (phase topology or flow regime), different interacting phases and/or constituents within the various modules of the system. Modeling guidelines are an outcome of the analysis and issued once the assessment is completed. These guidelines ensure that design verification and licensing activities comply with Regulatory Guide 1.203 requirements for modeling consistency. The guidelines define the appropriate use of the EM and provide the limits of the EM applicability.

In this work, the focus has been given to the capability of RELAP5-3D to model multi-dimensional flow. Section 2 presents the objectives of the assessment and describes the multi-staged approach to achieve those goals. At this initial stage simple canonical problems are identified in Section 3 and preliminary results of the assessment are presented in Section 4. The objective of this initial assessment is therefore to define the minimum set of requirements to assess the adequacy of the RELAP5-3D multidimensional flow capability and it is the primary objective of this paper.

2. MULTI-DIMENSIONAL FLOW ASSESSMENT SUITE OBJECTIVES

The primary objective of this work was to perform the initial stage of a bottom-up verification and validation of the selected code capabilities in modeling multi-dimensional flow. Following the hierarchical view suggested in Section 1, the first step of the assessment focuses on the "domain analysis." More specifically the objective is to verify how the code solves the transport of quantities in the fields of interest; i.e., the multidimensional distribution of mass, energy and momentum in geometries of interest. The key metrics for the adequacy judgment are measures of temporal and spatial convergence, accuracy and robustness.

The general purpose code RELAP5-3D is used as the basis for the EM of interest. The premise is that the code has been developed specifically to handle the complex three-dimensional flow that may occur in nuclear power plants when subjected to a variety of postulated events. However, this code feature has not yet been subjected to a rigorous assessment process, which would be needed to provide the desired confidence in its capabilities. This analysis is intended to cover this gap in the assessment.

The assessment has been organized in a staged fashion. At each stage the assessment objective moves up in the hierarchical tiers of the system processes. Simple processes are verified first before examining the interaction of different processes (integration) among the sub-tier in the tier above.

In the assessment process, modeling guidance is developed and code capabilities and shortcomings are identified. Same modeling guidance will be applied and further challenged as the assessment proceeds toward more complex integration of the processes at the lower tier of hierarchy. If this exercise is systematically conducted following this bottom-up and top down cycle in the assessment, the ultimate objective of consistency and completeness is attainable. More on the issue of completeness and consistency is provided in Section 5.

3. CONSIDERED CANONICAL PROBLEM

Following the staged bottom-up approach of the assessment, canonical problems are selected first, followed by a series of experimental facilities, starting with single phase adiabatic mixing and rationally add layers of process complexity. Analysis of the simulation of experimental test facilities is the subject of potential future work efforts. Some are common tests used in the literature or already considered as verification cases in the RELAP5-3D manual. Some new problems were added as part of this assessment. The problems are briefly introduced below:

<u>CP01: Water over Steam in a Pipe</u>

This problem is taken from the RELAP5-3D Developmental Assessment [3]. A cylindrical volume is nodalized in all three dimensions, with the vertical dimension being the longest. As an initial state the top $1/3^{rd}$ portion of the pipe is filled with water and the lower $2/3^{rd}$ portion of the pipe is filled with steam. This is an unstable configuration and as soon as the transient begins the water will fall to the bottom of the pipe.

<u>CP02: Symmetric Bucket Filling and Emptying</u>

In this problem a bucket is divided into four azimuthal “slices”. The bucket is filled by adding water into one slice of the bucket. The water should fill the bucket symmetrically. When the bucket is filled it is then drained from one side. The water should empty symmetrically.

<u>CP03: Static Vessel Test</u>

Mahaffy originally suggested this problem for the assessment of TRAC-M [4]. The purpose of this problem is to test for anomalies in the 3D momentum transport terms that can result in spurious circulation patterns. It is an important test to assess the applicability of the EM for use on passive reactors. The setup consists of a PWR vessel connected via short, single-cell pipes to zero flow boundary conditions on the cold legs, and constant atmospheric pressure conditions on the hot legs. Under ideal conditions, the problem undergoes a brief transient to adjust the pressures to appropriate hydrostatic values and then settles into a steady configuration with no flow and a level water surface.

<u>CP04: Fluid Level Test</u>

This test is a variation of the previous test. The same geometry of CP03 is utilized, however the level of the vessel is initially set to two different heights, one for each side of the vessel. When the transient begins a sloshing motion of the water develops.

CP05: Gravity Wave in a Box

This problem is taken from the RELAP5-3D Developmental Assessment [3]. It consists of a volume that is nodalized in two dimensions, with one being longer (Figure 1). Initially the lower half of the volume is filled with water; however the distribution of the water is not at equilibrium. More water is placed on one side of the volume. As the transient starts the water will flow from the high side to the low in cyclical fashion.

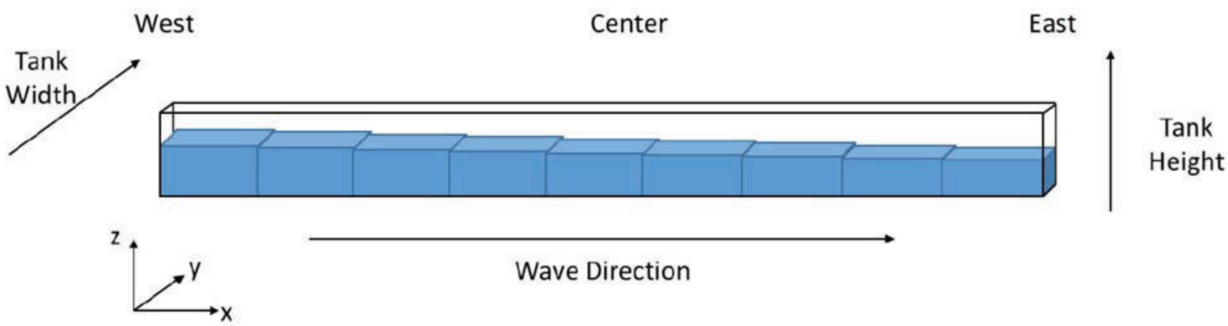

Figure 1 – Schematic of the gravity wave phenomenological canonical problem CP05

CP06: Faraday Waves

The problem was suggested as numerical benchmark by the author in 2004 [5]. When a liquid layer is subjected to a uniform external oscillation in the vertical direction and the forcing amplitude becomes sufficiently large, the free surface may be parametrically excited, leading to the generation of standing waves. These waves are called Faraday waves and typically the lowest resonance frequency of these waves is nearly half of the forcing oscillation frequency. The paper by Frepoli (2004) investigates the ability of general purpose thermal-hydraulic codes to predict the formation of Faraday waves in the annular downcomer of PWR vessels using the code's multi-dimensional modeling capabilities. A similar analysis is performed in this project and the results of the analysis are presented in a separate paper at this conference [6].

CP07: Analytic Potential Flow Solution

Analytical potential flow solutions for single-phase flows are available for rather complex geometries in the literature, for example the 1973 paper by Yeh [7]. The analysis of the code capabilities or limitations thereof to approximate potential flow is performed in this project for the RELAP-3D. Results of the analysis are presented in a separate paper presented at this conference [8].

4. SELECTED RESULTS

At the present time, the analysis has been completed for the first stage of the multi-staged approach outlined in Section 2. Stage 1 considered the seven canonical problems presented in Section 3. A few sample results are presented here for CP01 through CP05.

Canonical Problems CP01 through CP05 can be described as simple multidimensional flow transients occurring when an initially stagnant liquid volume in a partially filled container or vessel is perturbed from its initial state by some sort of instability at the interface. Each problem is unique in some aspects but the processes considered could be encountered in combination in more complex two-phase problems. Selected results are presented in the next subsections with the purpose of identifying modeling guidance or in some cases highlighting code limitations or shortcomings which should be considered by the developers to increase the fidelity of the code.

The following metrics are considered for the adequacy of the solution. The metrics are expressed by answering the following three key questions:

1) Does the numerical solution satisfy theoretical expectations or hypotheses?
2) Does the numerical solution preserve symmetries when the solution is anticipated to be symmetric?
3) Is the solution sensitive to modeling choices? If so, can modeling guidance be developed to control the behavior and ensure consistency?

4.1 Benchmark Accuracy and Trends

Each of the canonical problems presents physical features for which analytical solutions or trends can be anticipated.

CP01 is the classic Rayleigh-Taylor (R-T) instability extensively discussed in the literature ([9], [10], [11]). In this problem the top 1/3 of a cylindrical vessel is assumed to be initially occupied by liquid. The bottom 2/3rd are filled with gas (saturated steam). The liquid slug is expected to fall to the bottom 1/3rd while the gas replaces the liquid and fills the top 2/3rd.

The details of the development and evolution of the instability at the interface are beyond the resolution of the RELAP5-3D model considered here, however the code should be able to reproduce some key 'macroscopic' processes that enable the top 1/3rd height liquid slug to drop from the top of the vessel to the bottom in some time period (overturn time). The diameter of the vessel is assumed to be rather large (D=1.128 m). This is large compared to the size of bubble that can form in the liquid for example which provides a significant degree of freedom for the liquid and gas phases to move within the vessel with minimal interaction with the wall.

A lower bound for the replacing time was estimated assuming the liquid layer (slug) drops to the bottom of the vessel in free fall (hypothesis 1). The liquid replacing time was then estimated from the following equation:

$$t_1 = \sqrt{\frac{2h_{gas}}{g}} = 0.752s \tag{1}$$

In reality there must be some interaction between the phases, which slows down the free fall that will cause the replacing time to be longer than the lower bound provided by Eq. (1). Different processes were postulated to describe the scenario (hypotheses 2, 3 and 4).

In one scenario (hypothesis 2) the estimated replacing time was derived assuming the gas penetrates the liquid layer from the bottom as a single Taylor bubble in the center while liquid falls as film at the wall. Hypothesis 3 is based on a detailed analysis of the R-T instability which originates from ripples generated at the phase interface and then evolves into dripping filaments of liquid and falling droplets refilling the bottom over time. The presentation of the derivation of the governing equations is beyond the scope of the paper, however the theory can be found in [11] and [10]. Another possible scenario (hypothesis 4) is to postulate the development of an inverted annular flow where the liquid collects at the center of the cylinder and falls while the gas flow is countercurrent around it. Other processes could be considered. The analysis here considered the most plausible.

For the inverted annular flow hypothesis, a coordinate system with the vertical axis directed downward is assumed. The equation of motion can be simplified to the following momentum equation:

$$\frac{d\left(\rho_l u_l\right)}{dt} = F_g - F_i \tag{2}$$

Where F_g and F_i are respectively the gravity body force per unit volume and the interfacial drag force per unit volume:

$$\begin{aligned} F_g &= g\Delta\rho \\ F_i &= C_i\left|u_l - u_g\right|\left(u_l - u_g\right) \end{aligned} \tag{3}$$

The expression for the interfacial drag coefficient, C_i, can be found in the literature and the derivation is omitted here. Eq. (2) is then integrated. Assuming liquid is incompressible the calculated velocity of the liquid is presented in Figure 2. The maximum liquid downflow is limited by the interfacial drag (terminal velocity) or Counter Current Flow Limit (CCFL), whichever occurs first.

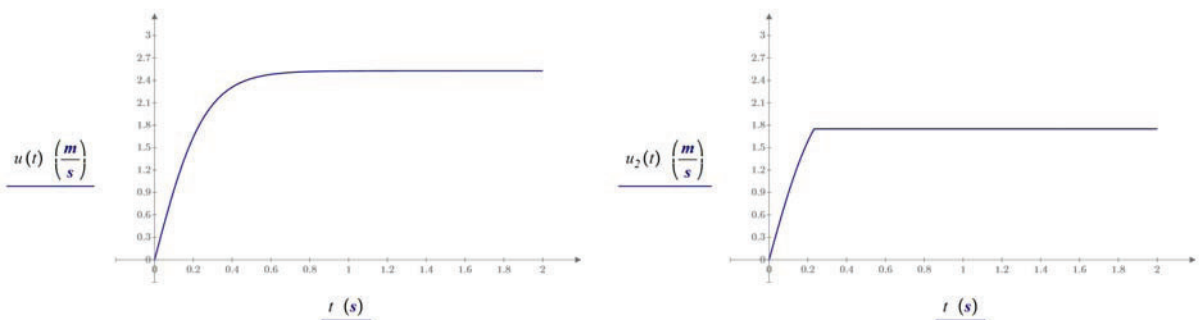

Figure 2 - Estimated downflow liquid velocity in annular flow regime (P=413 kPa on the left and P=6800 kPa on the right)

Under the postulated scenario, depending on the conditions (assumed void fraction and pressure), the turnover time ranges between 0.964 to 1.240 seconds.

Table I compares the RELAP5-3D predictions with different meshes (pressure is 413 kPa in all cases) to the analytical solution obtained from the different hypotheses. A representative characteristic time was selected for this transient. This is the time required to move 75% of the total liquid volume to the bottom of the vessel. RELAP5-3D predicts times which are closer to the upper bound analytical estimates.

Table I – Mesh Sensitivity Studies

Mesh $N_r \times N_\Theta \times N_z$	Time to 75% Hypothesis 1 (sec)	Time to 75% Hypothesis 2 (sec)	Time to 75% Hypothesis 3 (sec)	Time to 75% Hypothesis 4 (sec)	Time to 75% Hypothesis 4 with CCFL (sec)	Time to 75% RELAP5-3D (sec)
1 x 1 x 9	0.704	0.895	3.920	0.767	0.767	5.6
2 x 1 x 9						4.0
2 x 4 x 9						3.68
9 x 1 x 9						4.04
9 x 8 x 9						3.36
9 x 8 x 90						3.48

Figure 3 shows the predicted Collapsed Liquid Level (CLL) for the various cell stack for the 3D solution and how it compares to the 1D solutions (black line). The 3D model enables a faster and more monotonic liquid turnover.

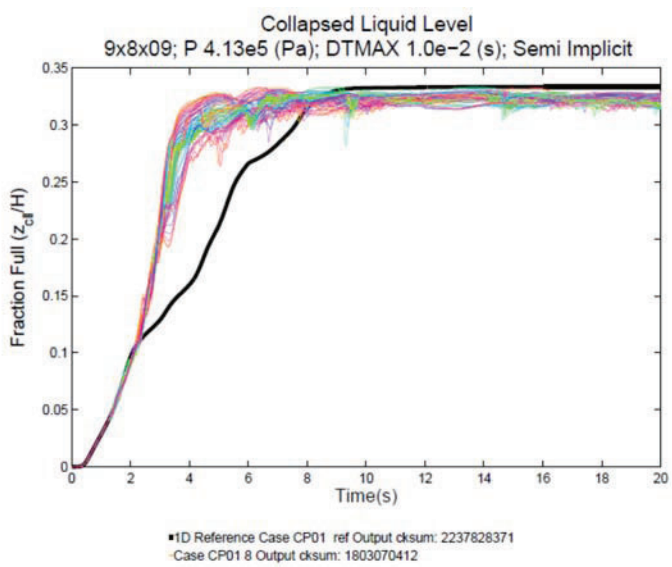

Figure 3 – CP01 Predicted Collapsed Liquid Level for the various cell stacks for the 1D and 3D solutions (fine mesh on the left and coarse mesh on the right)

CP01 is a highly dynamic and complex problem. At the opposite range of complexity, CP03 is a simple static vessel. The success metric here is a measure of the error relative to the hydrostatic solution. Theoretically, the horizontal pressure gradient in a static vessel is zero. The error at any given time from the hydrostatic solution can be computed as follows:

$$\varepsilon_P(t) = \sum_{i=1}^{N} \frac{\left| P_i(t) - P_0 - \rho_{l,i}\, g\,(H - z_i) \right|}{P_0 + \rho_l\, g\,(H - z_i)} \tag{4}$$

The pressure error is shown in Figure 4. The error in pressure results in a residual velocity field which is also shown in Figure 4.

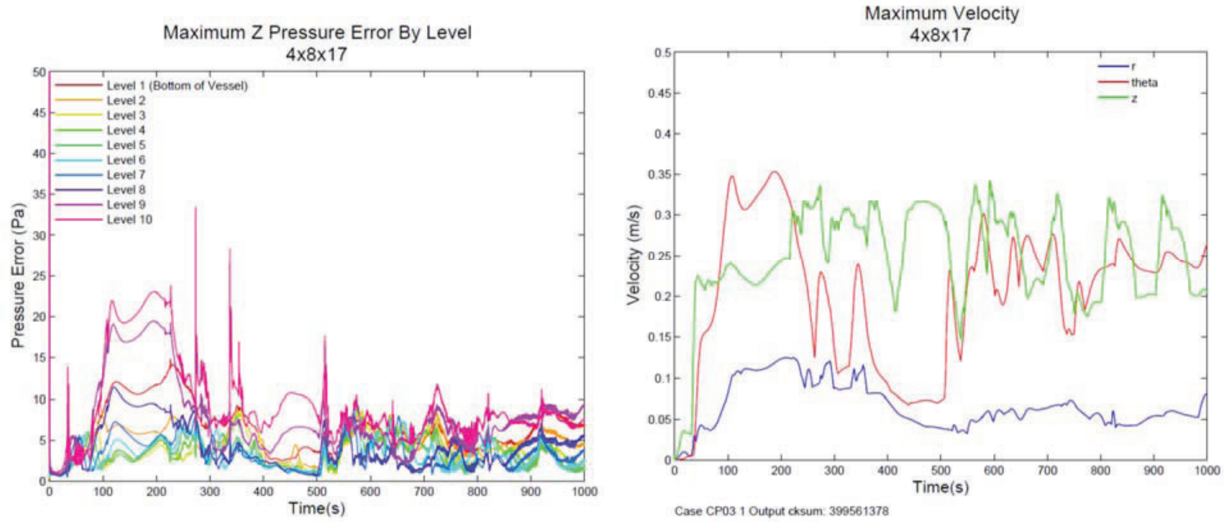

Figure 4 - Maximum Pressure Error Relative to Hydrostatic Pressure at Each Level (CP03) (on the left) and Maximum Velocity (CP03) (on the right)

4.2 Symmetry Checks

The solution is expected to be symmetric where the geometry, boundary conditions and mesh are designed to be symmetric. Symmetry checks on the solution are therefore performed. Figure 5 shows the predicted collapsed liquid level in the eight cell stacks which originates in 2x4x9 mesh of CP01. The curves with one color are expected to respond identically during the transient and collapse on each other, however a degree of asymmetry is observed. The asymmetry likely originates from numeric and discretization errors.

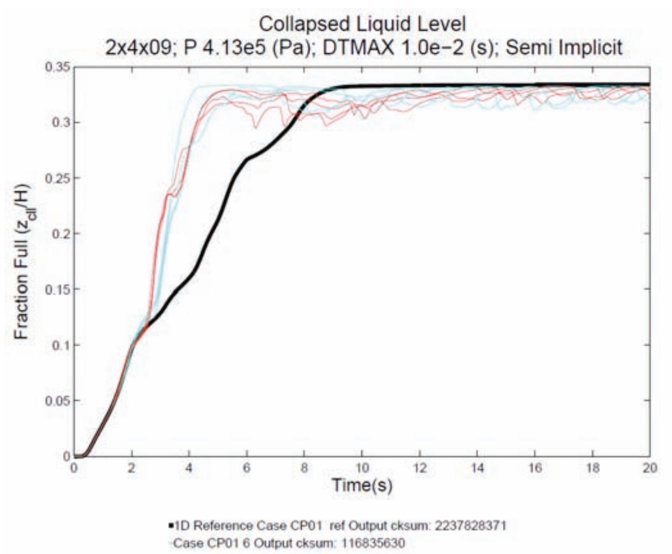

Figure 5 – Symmetry analysis (CP01)

Similarly, the filling bucket problem includes four segments which should fill and drain symmetrically. However, a small degree of asymmetry in the transverse flow is computed by the code which is an anomaly.

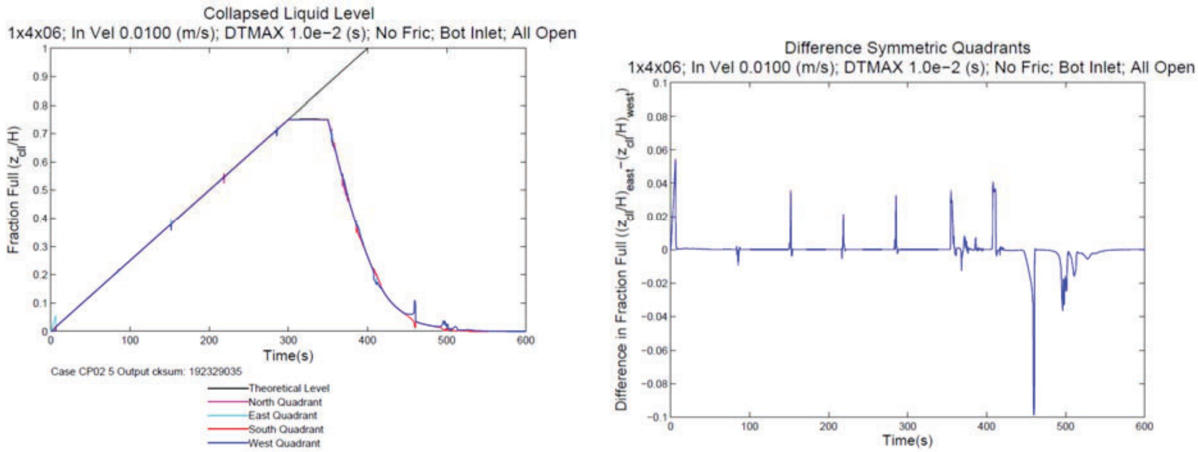

Figure 6 - Level Difference for the Symmetric Quadrants (E-W) (CP02)

4.3 Mesh Rotation Invariance Checks

For a 3D mesh, the solution should be invariant to the 90-degree rotation of the axis, or in other words to the order of axis selected by the user to set up the same problem. CP05 is suited to verify this topological issue because of its long aspect ratio. The model can be set-up assuming the axes as shown in Figure 1. The solution should be identical considering all possible permutations of the axes orientation, granted gravity needs to be oriented in the proper axis (z in the figure below). Figure 7 shows that the rotational invariance is preserved to a high degree of accuracy.

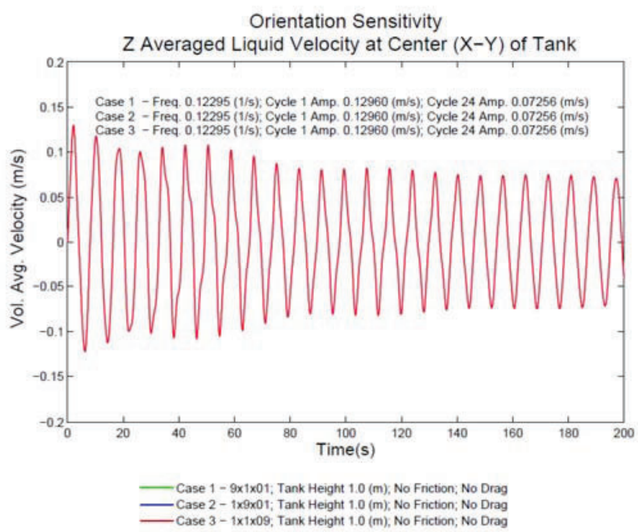

Figure 7 – Average velocity in the middle of the channel along the sloshing direction (CP05)

4.4 Spatial Discretization Studies

Mesh studies are conducted for most of the problems considered. The effect is significant in some cases. Note that the degree of empiricism in the multi-phase constitutive relationships in system codes renders traditional grid convergence, as realized with single phase CFD codes, to be rarely demonstrated. The objective in this case is consistency; with a goal of developing scalable, physically based modeling guidelines on how to best capture the physics of the problem.

For example it was found that only two radial nodes are necessary to significantly improve the solution relative to the 1D case for the CP01 (water over steam problem). Further refinement of the mesh did not appear to significantly improve the results. This indicates that the key is to have sufficient degrees of freedom to promote inter-volume counter current flow, which appears inhibited in the 1D model. Figure 8 shows the comparison of the predicted collapsed liquid level in the different cell stacks for the 1D solution (in black) and 3D solutions (the lines in color).

Figure 8 on the left shows the predicted Collapsed Liquid Level (CLL) of the bottom three nodes normalized to the full mesh height for the various cell stacks for the 1D and 3D solutions. When the transient is complete and all the liquid has reached the bottom of the pipe this level should be 0.33. The 3D model enables a faster and more monotonic liquid turnover. Note that the crude 2D model with only two rings ($N_r \times N_\Theta \times N_z = 2\times 1\times 9$) was sufficient to capture most of the features observed with the finest two-dimensional mesh ($N_r \times N_\Theta \times N_z = 9\times 8\times 9$).

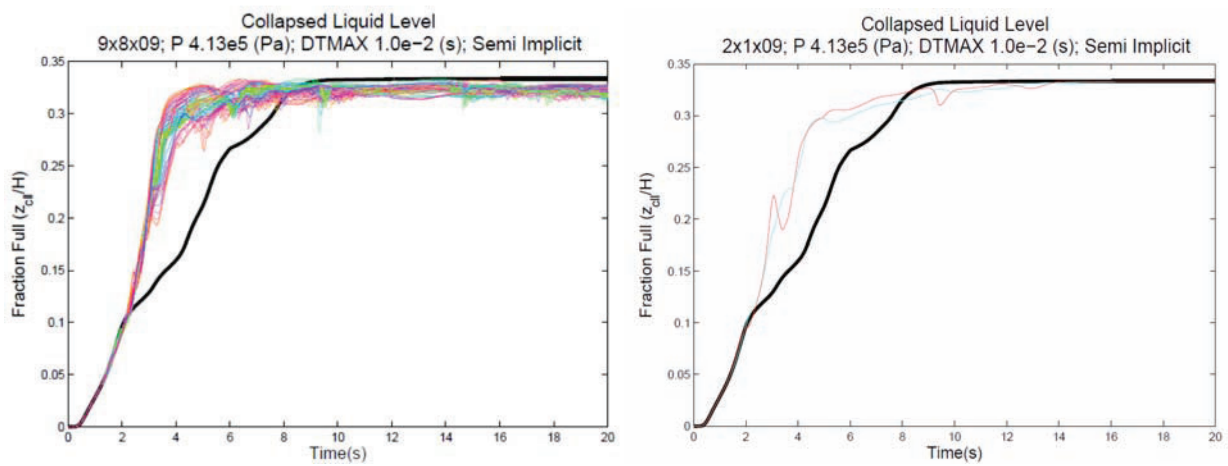

Figure 8 – CP01 Predicted Collapsed Liquid Level for the various cell stack for the 1D and 3D solutions (fine mesh on the left and coarse mesh on the right)

When the mesh is refined in the vertical direction, increasing from 9 cells to 90 cells, a slower draining is initially observed followed by a greater acceleration resulting in the time to fill the lower third of the vessel being about the same (Figure 9).

CP04 can be used to define the minimum nodalization requirements to capture a sloshing motion. The acceptance criteria is the capability of the simulation to describe a regular periodic sloshing motion. The sloshing is in this case the fundamental standing wave in a square box. The wave number of a standing wave in a square section tank is in general given by:

$$k_{m,n} = \sqrt{\left(m\frac{\pi}{L_x}\right)^2 + \left(n\frac{\pi}{L_y}\right)^2} \tag{5}$$

Where *m* and *n* are the number of nodes in x and y direction, respectively, and L_x and L_y are the length of the sides of the box. For a square tank, $L_x = L_y \equiv L$ and the fundamental wave mode is $k_0 = k_{0,1}$.

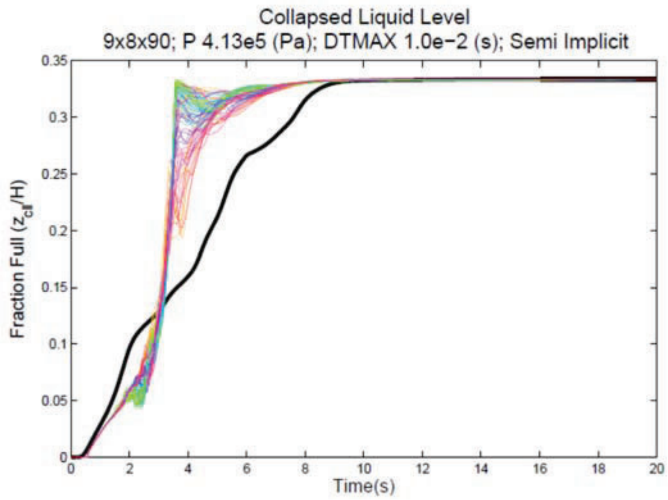

Figure 9 - Nodalization Study (CP01)

Given the CP04 geometry, the frequency for the sloshing dominant mode is given by (considering $\tanh\left(k_0 H\right) \sim 1.0$):

$$
\begin{aligned}
f_0 &= \frac{1}{2\pi}\sqrt{\frac{\pi g}{L}} = 0.442 s^{-1} \\
T_0 &= \frac{1}{f_0} = 2.264 s \\
k_0 &= \frac{\pi}{L} = 0.785 m^{-1} \\
\lambda_0 &= \frac{2\pi}{k_0} = 2L
\end{aligned}
\qquad (6)
$$

A general observation is that the tendency of the code is to artificially disperse the wave motion. More specifically the predicted sloshing frequency ranges between 0.29 to 0.34 Hz based on the mesh, which is significantly lower than the theoretical value (0.442 Hz). The dispersion decreases, as the mesh is refined. However, even for the most detailed mesh considered in the analysis (8 nodes along the sloshing direction) the predicted frequency is 30% lower than the theoretical value.

Figure 10 shows that 2 nodes are sufficient to capture the sloshing to some degree. This gives a criterion for the maximum node size needed to capture a wave motion in direction *x*:

$$\Delta x^* = \frac{\Delta x}{\lambda} < \frac{1}{4} \qquad (7)$$

Or more in general:

$$\Delta x_i k_i < \frac{\pi}{2} \qquad (8)$$

Where k_i is the component along the coordinate x_i of the instability wave number.

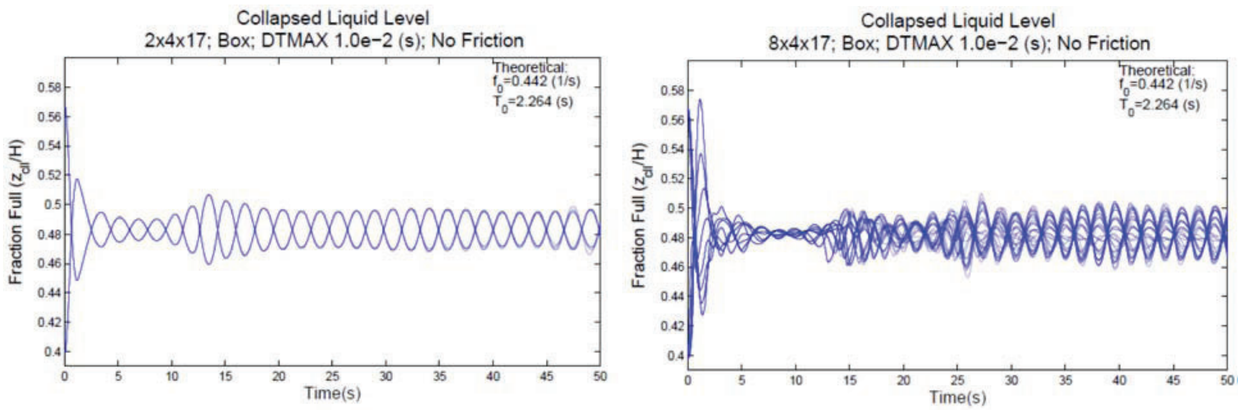

Figure 10 - Collapsed Liquid Levels (CP04)

4.5 Time Integration Studies

Time step size sensitivities are conducted for all the problems considered. In Figure 11, the results for problem CP04, the level settling problem, are shown. As time step is increased the resolution of the sloshing deteriorated. Note that for this case the time step size was kept at its maximum (dt = 10 ms) which leads to the conclusion that the solution is considered an acceptable solution at each time step by the code. However a significant loss of accuracy is observed when the time step size is increased from 1 ms to 10 ms. The solution is not acceptable when the time step size is increased further to 100 ms (Case CP04 8). In this last case, time step size was sometimes reduced automatically by the code during the transient as shown at the bottom of Figure 11.

A possible criterion can be defined by comparing the time step size with the fundamental frequency associated with the instability that the model is intended to simulate. A suggested criterion is:

$$\Delta t^* = \frac{\Delta t}{T} = f_n \Delta t < 0.003 \tag{9}$$

Where T and f_n are respectively the time period and frequency associated with the phenomena that is intended to be captured.

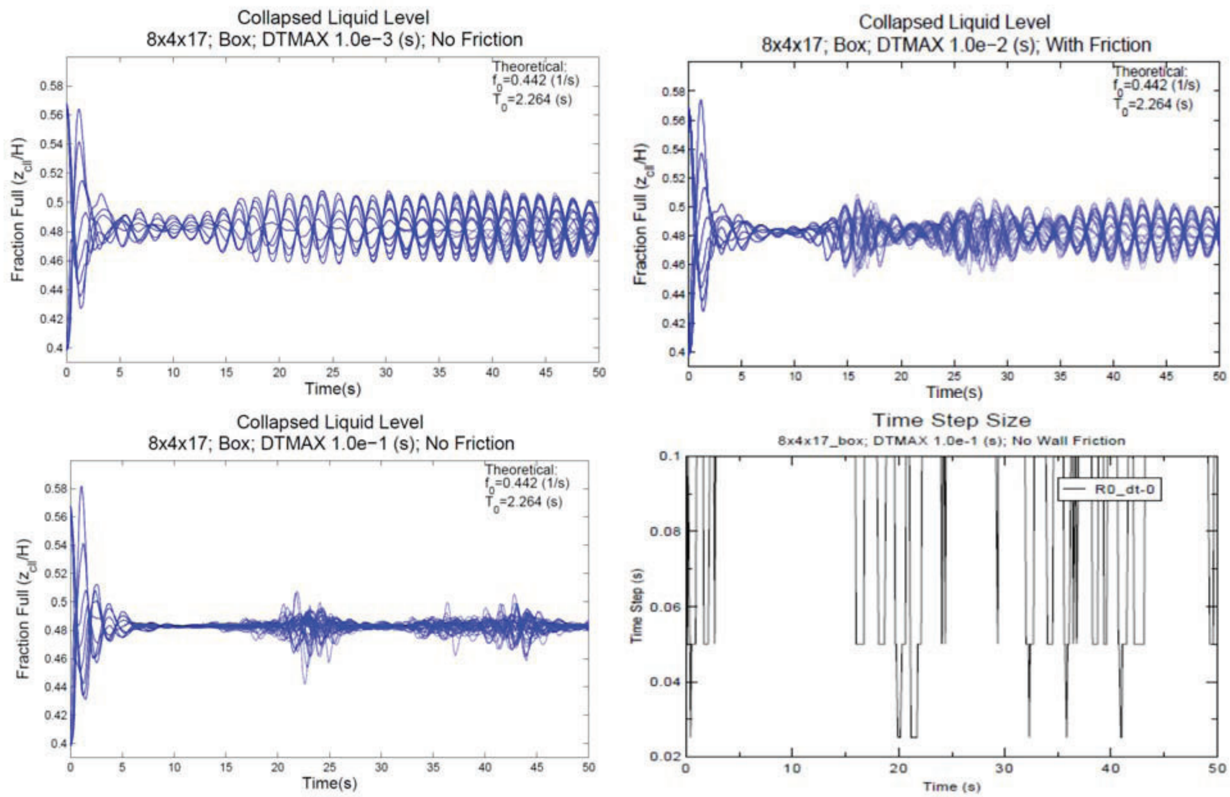

Figure 11 – CP04 Predicted Collapsed Liquid Levels using different time step size (in blue) and time step size history for the case with dt=0.1sec (CP04)

5. COMPLETENESS AND CONSISTENCY

One of the objectives of the assessment of an analytical tool is to achieve ‘engineering’ completeness and consistency relative to the problem solved. The word ‘engineering’ is included since while true completeness is the aim in solving complex problems, it is often unattainable as even the underlying mathematical model is often an incomplete characterization of reality.

As a result, in engineering, the deductive element involves a reasoned evaluation that combines observation, modeling and simulation, and a rigorous system decomposition of the problem followed by the development of an evaluation methodology to address the revealed analytical challenges. This is the purpose of the assessment strategy presented in this paper.

Given the considerations above, mathematical models of the physics involved have been developed and are postulated for various problems. A computational model of each of the problems is setup with the code and different numerical solutions are obtained by testing various modeling choices. The degree of fidelity of the solution is judged on a metric which is distilled through answering the simple questions presented in Table II.

Table II – Metrics for Adequacy Determination

Does the numerical solution satisfy theoretical expectations or hypotheses?	Solutions are plausible considering the limitations of resolution and degree of empiricism contained in system codes. For this stand point the solutions was judged overall REASONABLE with some exceptions. For instance the ‘spurious’ flow predicted for the static test could be judged

	MINIMAL or INSUFFICIENT for specific applications.
Does the numerical solution preserve symmetries when solution is anticipated to be symmetric?	The degree of numerically induced asymmetries exceeds the desired outcome since flow anomalies could be of the same order of the solution itself. On this metric the adequacy is judged MINIMAL.
Is the solution sensitive to modeling choices? In such case, can modeling guidance be developed to control the behavior and ensure consistency?	Yes. The sensitivity is high which enforce the need for developing rigorous modeling guidelines to achieve the desired level of consistency.

Guidance on modeling options was derived from this initial assessment of basic fluid problems. For instance, it was determined that for situations in which an unstable inverted pool is created in a vertical channel, a multidimensional description is necessary to properly capture the evolution of the transient. However, the relevant need is to have sufficient degrees of freedom in the problem to enable counter current flow to occur (two horizontal nodes as a minimum).

Mesh and time step size sensitivities indicate that the mesh size and time step used to solve for instabilities occurring at the interface of a liquid layer in a vessel or tank should be limited. Simple criteria were developed from the analysis and expressed by Eqs. (8) and (9). These criteria can be further confirmed with additional studies, but are code specific and cannot be generalized.

6. CONCLUSIONS

The paper illustrates the design of a structured bottom-up review of a system code for a set of phenomena. In this case, the question is to judge the capability of RELAP-3D to model multi-dimensional flow. The first step in the assessment process is to confirm the adequacy of the numerical model to properly represent the mathematical model by tracing the conserved field properties, such as mass, momentum, and/or energy. This is described as “domain analysis”.

Fundamental multidimensional canonical problems are constructed to achieve the objective. The minimum set of requirements to ensure RELAP5-3D is able to capture the selected processes with a reasonable fidelity is inferred from the analysis.

Shortcomings or limitations in the implementation of the multidimensional component in RELAP5-3D have been identified. For instance the solution, as demonstrated in Section 4.2, is not respecting criteria of symmetry to a satisfactory level and further investigation on this issue is recommended.

7. REFERENCES

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