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ABSTRACT

The RELAP5-3D computer program has been improved with regard to its nearly-implicit numerical scheme for two-phase flow and single-phase flow. Changes were made to the nearly-implicit numerical scheme finite difference momentum equations as follows: (1) added the velocity flip-flop mass/energy error mitigation logic, (2) added the modified Henry-Fauske choking model, (3) used the new time void fraction in the horizontal stratification force terms and gravity head, and (4) used an implicit form of the artificial viscosity. The code modifications allow the nearly-implicit numerical scheme to be more implicit and lead to enhanced numerical stability.

INTRODUCTION

The RELAP5 series of codes has been developed at the Idaho National Engineering and Environmental Laboratory for over 25 years under sponsorship of the U. S. Department of Energy, the U. S. Nuclear Regulatory Commission, members of the International Code Assessment and Applications Program, members of the Code Applications and Maintenance Program, and members of the International RELAP5 Users Group. Specific world-wide applications of the code have included simulations of transients of light water reactor systems such as loss of coolant, anticipated transients without scram, and operational transients such as loss of feedwater, loss of offsite power, station blackout, and turbine trip. RELAP5-3D (Ref. 1), the latest in the series of RELAP5 codes, is a highly generic world-wide used code that, in addition to calculating the behavior of a reactor coolant system during a transient, can be used for simulation of a wide variety of hydraulic and thermal transients in both nuclear and nonnuclear systems involving mixtures of vapor, liquid, noncondensable gases, and nonvolatile solute. The 3D capability in RELAP5-3D includes 3D hydrodynamics and 3D neutron kinetics (the 3D neutronics is based on the NESTLE code).

RELAP5-3D is also used in an ATHENA-3D (Ref. 2) configuration that includes magneto-hydrodynamics and many thermodynamic working fluid properties besides water (such as gases, liquid metals, and molten salts). The ATHENA-3D configuration is currently used primarily in Generation IV reactor applications, space reactor applications, and nuclear fusion applications. RELAP5-3D is also used in a SCDAP/RELAP5-3D (Ref. 3) configuration that is designed to calculate, for severe accident situations, the overall reactor coolant system thermal-hydraulic response, core damage progression, and reactor vessel heatup and damage. RELAP5-3D (also true of ATHENA-3D and SCDAP/RELAP5-3D) is also used in an integrated code system configuration consisting of RELAP5-3D and other codes such as FLUENT, CFX, and CONTAIN. The coupling of the codes in this configuration is coordinated using an executive program (Ref. 4) in concert with the Parallel Virtual Machine (PVM) message passing software. The coupling can be done explicitly or semi-implicitly. For example, the FLUENT/RELAP5-3D (Ref. 5) coupling configuration is designed to perform detailed 3D analyses using FLUENT's capability while the boundary conditions required by the FLUENT calculation are provided by the balance-of-system model created using RELAP5-3D. The FLUENT/RELAP5-3D coupling configuration is currently used primarily in Generation IV reactor applications. RELAP5-3D is also used for the thermal-hydraulic module in the real-time nuclear plant simulation code RELAP5-R/T (Refs. 6, 7, 8), which is used in training simulators at nuclear power plants around the world. There is also a visualization system for the various RELAP5-3D configurations, which is called the RELAP5-3D Graphical User Interface (RGUI) (Ref. 9).

This paper discusses recent improvements to the material Courant-violating nearly-implicit advancement scheme (Ref. 10), which is used in all the RELAP5-3D configurations.

VELOCITY FLIP-FLOP

There are mass and energy errors that the numerically conservative form of differencing cannot remove. The convective terms in the field equations are computed with donored properties determined by the direction of phasic velocities. There are times that the final velocities may differ in directions from the explicit velocities used to define the donored properties. This may result in mass/energy errors due to incorrect properties used in the numerical scheme. The term 'velocity flip-flop' refers to the situation in which the final velocities and the explicit velocities differ in sign. In the RELAP5-3D numerical scheme, the pressures and final velocities are calculated using the donor properties based on the explicit velocities (for both the semi-implicit scheme and the nearly-implicit scheme). The velocity flip-flop implies that inconsistent donor properties were used for the pressure/velocity computation and the final mass/energy computation. This may result in bad pressure, velocity, and energy solutions and large mass errors. Thus a mitigation scheme is employed to detect and fix errors of this type. The mitigation scheme is discussed in Volume I, Section 8.2 of the RELAP5-3D manual (Ref. 1). The mitigation scheme has been used for the semi-implicit scheme, and it has recently been included in the nearly-implicit scheme.

The standard assessment problems were used to ensure the coding was correct.

MODIFIED HENRY-FAUSKE CHOKING MODEL

The modified Henry-Fauske choking model is an optional choking model to the default Ransom-Trapp choking model in RELAP5-3D. The modified Henry-Fauske choking model is applicable when the experimental break configuration is a thin orifice plate (thickness about 10 mm) and the flow conditions are slightly subcooled liquid. For these conditions, the amount of thermal nonequilibrium at the throat present in the default Ransom-Trapp choking model is insufficient to allow the code-calculated critical flow rates to match the critical flow rates observed in the experiments. A feature of the modified Henry-Fauske choking model that allows good comparison to experiments for these conditions is the thermal nonequilibrium factor. As with the semi-implicit scheme, the nearly-implicit scheme momentum equations were modified to impose the modified Henry-Fauske choking equation if the junction is choked and the modified Henry-Fauske choking model option is selected. This involved storing the proper terms in the correct variables.

The standard choking assessment problems were used to ensure the coding was correct.

HORIZONTAL STRATIFICATION FORCE TERMS AND GRAVITY HEAD

The unique feature of the nearly-implicit scheme's finite difference momentum equations allows the horizontal stratification force terms and gravity head to be calculated using the new time void fraction. The unique feature is that the new time phasic velocities are solved in one step. In the original nearly-implicit scheme, the new time pressure gradient terms in the momentum equations are written in terms of the new time pressures in the volumes at the two ends of each junction. These new time pressures in turn can be written in terms of the new time phasic velocities in the junctions attached to each volume. These new time pressure-velocity relations are then used to eliminate the new time pressure gradient terms in the momentum equations and replace the terms with the new time phasic velocities. In this improved nearly-implicit scheme, the horizontal stratification force void gradient terms and gravity head void fraction terms in the momentum equations are written in terms of the new time void fractions in the volumes at the two ends of each junction. These new time void fractions in turn can be written in terms of the new time phasic velocities in the junctions attached to each volume. These new time void fraction-velocity relations are then used to eliminate the new time void fraction gradient terms and new time void fraction terms in the momentum equations and replace the terms with the new time phasic velocities.

The standard assessment problems were used to ensure the coding was correct. An example of one these assessment problems is next discussed. It is the horizontally stratified countercurrent flow problem. It is a conceptual problem involving a horizontal pipe closed at both ends with a linearly graduated liquid level. Due to gravitational head difference, the liquid tends to flow from the higher-level side to the lower-level side. The vapor is forced to flow in the opposite direction from the liquid. A countercurrent flow is developed. The predicted history of the liquid and vapor junction velocities at three locations (left, middle, and right) is shown in Figures 1 and 2. These calculations were run with reduced interphase drag and reduced virtual mass so as to remove the effect of these models on the calculation. The problem time step size was 0.05 sec (ramped from 0.001 sec to 0.05 sec during first 5 sec). For the case of a 1-D horizontal circular pipe, the wave speed is given by expressions in References 11 and 12. For this problem, the theoretical and code calculated wave speed time step size is approximately 0.36 sec. Since the problem time step size is less than the wave speed time step size, the plots are fairly smooth for both the semi-implicit scheme and the original nearly-implicit scheme (Figures 1 and 2). When the problem time step size is increased to be larger than the wave speed time step size (i.e., problem time step size of 0.5 sec), some problems exist. In both the semi-implicit scheme and the original nearly-implicit scheme, oscillations occur (see Figures 3 and 4). When the improved nearly-implicit scheme is used (used new time void fraction in horizontal stratification force terms and gravity head), the oscillations are removed and the plots are fairly smooth again (see Figures 5 and 6).

ARTIFICIAL VISCOSITY

The convective (momentum flux, spatial velocity gradient) terms in the momentum equations are approximated using a donor-like formulation that results in a centered velocity gradient term and a viscous-like term (numerical viscosity, artificial viscosity). The semi-implicit scheme uses this approximation, and previously the nearly-implicit scheme used just the centered velocity gradient term (this was fine for stability purposes since the term is implicit). The nearly-implicit scheme has now been changed to add in the viscous-like term (numerical viscosity, artificial viscosity) in an implicit fashion. This was achieved as follows:
First, the semi-implicit scheme was modified to replace the numerical viscosity form with a true donor-cell form. This was done for programming convenience; the two formulations are mathematically equivalent to each other. Next, the nearly-implicit scheme was also modified to use a true donor-cell form (i.e., donored velocity times centered velocity). For this, both the centered velocity and the donored velocity for each volume were expressed at new time in a linearized fashion.

The standard assessment problems were used to ensure the coding was correct.

CONCLUSIONS

Changes were recently made to the nearly-implicit numerical scheme finite difference momentum equations. This paper has discussed the details of these changes and has presented some results. The changes allow the nearly-implicit numerical scheme to be more implicit and lead to enhanced numerical stability.

ACKNOWLEDGMENTS

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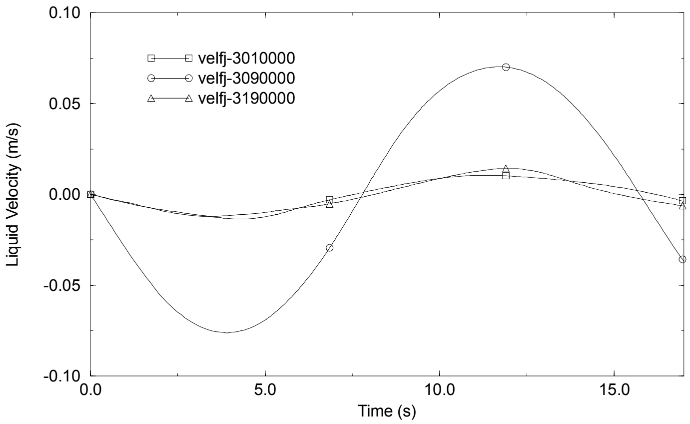

Figure 1. Junction liquid velocities at three locations (dt = 0.05 sec).

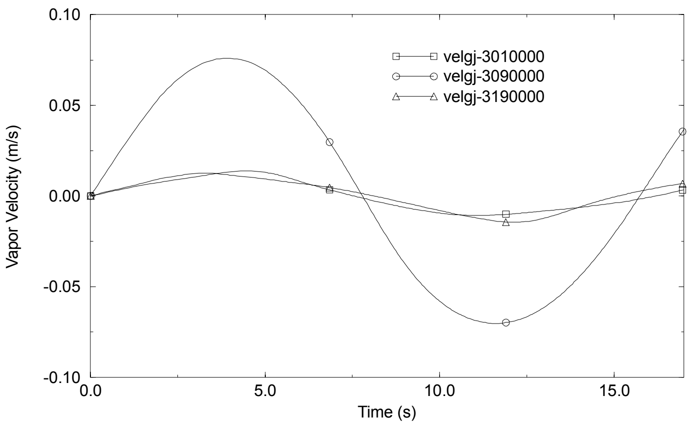

Figure 2. Junction vapor velocities at three locations (dt = 0.05 sec).

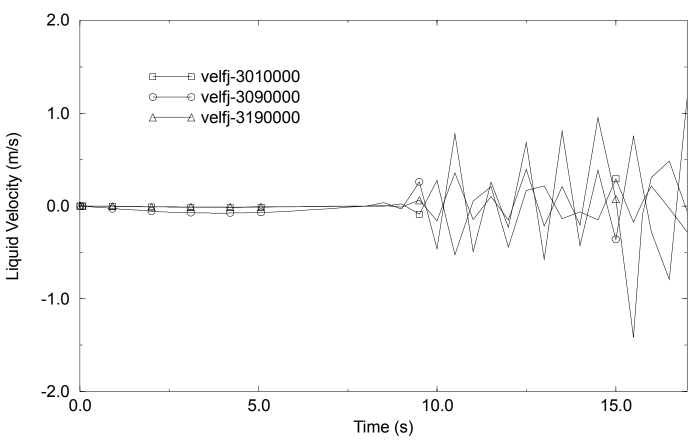

Figure 3. Junction liquid velocities at three locations (dt = 0.5 sec).

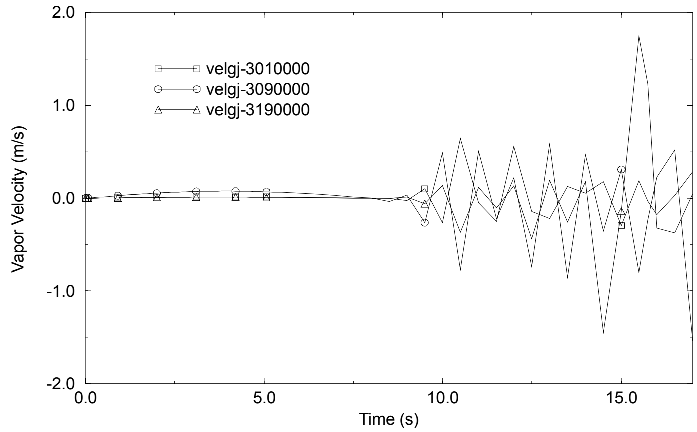

Figure 4. Junction vapor velocities at three locations (dt = 0.5 sec).

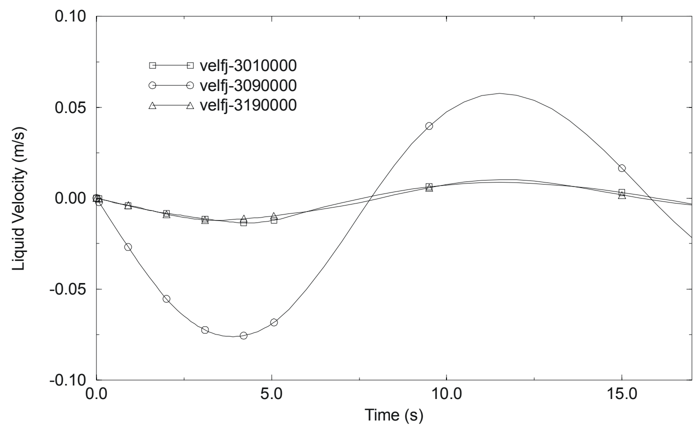

Figure 5. Junction liquid velocities at three locations (dt = 0.5 sec, implicit horizontal stratification force and gravity head).

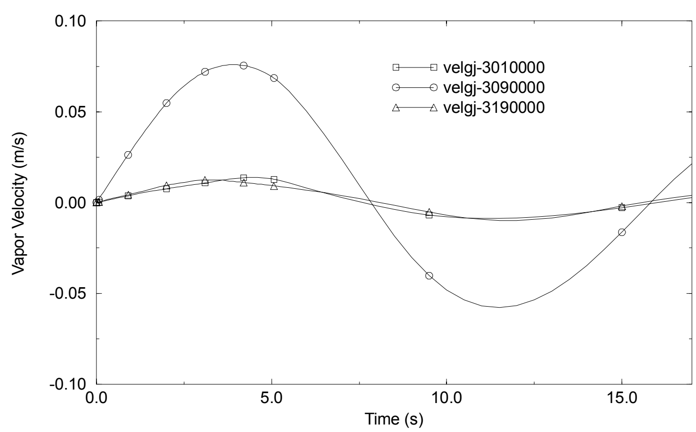

Figure 6. Junction vapor velocities at three locations (dt = 0.5 sec, implicit horizontal stratification force and gravity head).