Conservation of Fluid Mass and Energy by RELAP5-3D during a SBLOCA

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Abstract

Mass and energy balances were performed to check the accuracy of RELAP5-3D's solution during a loss-of-coolant accident initiated by a small break in a typical pressurized water reactor. Mass and energy balances were performed for the combined liquid and gas phases and the gas phase by itself. The analysis showed that RELAP5-3D adequately conserved mass and energy for the combined fluid and the gas phase.

Summary

Mass and energy balances were performed to check the accuracy of RELAP5-3D's solution during a loss-of-coolant accident initiated by a small break in a typical pressurized water reactor. Although mass and energy balances have been performed previously, balances were generally performed only for the combination of the liquid and gas phases. This analysis was unique in that the mass and energy balances of the gas phase were also considered.

Mass and energy balances were performed for the primary coolant system of a typical pressurized water reactor. The total mass and energy of the primary coolant system were obtained using two methods. First, total values were obtained by summing the mass and energy of each control volume in the system. Second, total values were obtained by integrating the mass and energy conservation equations. The total values from the two methods were then compared at the end of the simulation to check the overall accuracy of the code's solution.

The mass and energy balances showed that RELAP5-3D adequately conserved mass and energy for the combined fluid and the gas phase. Thus, the code also adequately conserved mass and energy for the liquid phase. The total mass values at the end of the simulation agreed within 0.04% for the combined fluid and within 0.3% for the gas phase. The total energy values agreed within 1.2% for the combined fluid and within 1.0% for the gas. Larger deviations were expected in the energy values because of approximations used in the energy equations, which are relatively complicated compared to the continuity equations.

1.0 Introduction

The RELAP5-3D computer code[1] was developed to simulate the thermal-hydraulic behavior of various reactor systems. The code contains a two-fluid model that enables it to simulate loss-of-coolant accidents. The code solves conservation equations for mass, energy, and momentum for both liquid and vapor phases. Users frequently perform mass and energy balances for the combination of the liquid and gas phases to provide confidence in the calculated results. Mass and energy balances for each phase have generally not been performed, but are required to fully test the two-phase solution provided by RELAP5-3D. Consequently, global mass and energy balances were performed for both phases during a small-break loss-of-coolant accident (SBLOCA) in a typical reactor to demonstrate the capabilities of the code.

Section 2 describes the equations used to obtain the global mass and energy values. The results of the global mass and energy balances are presented in Section 3. Conclusions and references are provided in Sections 4 and 5, respectively.

2.0 Balance Equations

Section 3.1 of the RELAP5-3D manual (Ref. 1) describes how the code solves the continuity, energy, and momentum equations. For convenience, the code uses sum and difference forms to solve the continuity and momentum equations and liquid and vapor forms to solve the energy equation.

The approach taken here is to obtain independent solutions to the mass and energy equations for the combined fluid and the vapor and to compare those results with the values obtained directly from the code. The momentum equations were not evaluated because of their complexity.

The total fluid mass, M, in a system can be written as

$$M = \sum_k M_k = \sum_k (\alpha_f \rho_f V)_k + \sum_k (\alpha_g \rho_g V)_k \ , \tag{1}$$

where α is the phasic volume fraction, ρ is the phasic density, V is the fluid volume, and the subscript k corresponds to the kth control volume in the system. Subscripts f and g correspond to the liquid and gas phases, respectively.

The total mass balance for the system can be written by combining Equations 3.1-2 and 3.1-3 from Volume 1 of the manual and integrating to obtain

$$M = M_0 + \int_0^t (\dot{m}_{in} - \dot{m}_{out}) dt \ , \tag{2}$$

where $\dot{m}$ is the combined mass flow rate of the liquid and gas, the subscripts in and out refer to the flow entering and leaving the system, t is time, and the subscript 0 refers to the initial time.

The right hand side of Equation 1 is evaluated by summing the liquid and gas masses in all the control volumes in the system using control variables. Similarly, control variables are used to evaluate the right hand side of Equation 2 by integrating the flows into and out of the system and adding the integrals to the initial mass, M_0. The comparison of the right hand sides of Equations 1 and 2 can then be used to check the total fluid mass calculated by the code.

A similar approach was used to perform the global mass balance on the gas phase. The resulting equations are

$$M_g = \sum_k M_{g\text{-}k} = \sum_k (\alpha_g \rho_g V)_k \tag{3}$$

and

$$M_g = M_{g\text{-}0} + \int_0^t (\dot{m}_{g\text{-}in} - \dot{m}_{g\text{-}out}) dt + \int_0^t \left(\sum_k (\Gamma V)_k \right) dt \ , \tag{4}$$

where Γ is the rate of vapor production per unit volume due to interfacial mass transfer. The comparison of the right hand sides of Equations 3 and 4 can then be used to check the total gas mass calculated by RELAP5-3D. Although not presented here, the total mass for the liquid phase can be obtained by subtracting the gas mass from that of the combined fluid.

The total internal energy of the fluid in the system, U, can be obtained as

$$U = \sum_k U_k = \sum_k (\alpha_f \rho_f u_f V)_k + \sum_k (\alpha_g \rho_g u_g V)_k ,$$ (5)

where u is the specific internal energy.

The total energy can also be estimated by integrating an approximate form of the energy equation. The resulting total energy is

$$U = U_0 + \int_0^t (\dot{m}_{in} h_{in} - \dot{m}_{out} h_{out})dt + \int_0^t \left(\sum_k Q_{w\text{-}k}\right)dt - \int_0^t \left(\sum_k \omega_k \tau_k\right)dt ,$$ (6)

where h is the specific enthalpy of the fluid flowing into or out of the system, Q_w is the total heat transfer from the walls surrounding the control volume into the fluid, and ω and τ represent the speed and torque of any shaft doing external work on a control volume. A minus sign is used in front of the shaft work term to account for the code's convention that the torque is that of the fluid on the shaft rather than the shaft on the fluid.

Equation 6 is approximate because terms associated with kinetic energy, potential energy, and viscous dissipation are neglected. The total energy of the fluid calculated by RELAP5-3D can be checked by comparing the right hand sides of Equations 5 and 6.

The total internal energy of the gas in the system, U_g, can be obtained as

$$U_g = \sum_k U_{g\text{-}k} = \sum_k (\alpha_g \rho_g u_g V)_k .$$ (7)

The code solves the phasic thermal energy equations given by Equations 3.1-11 and 3.1-12 of Volume 1 of the manual. The thermal energy for the gas equation can be approximated as

$$U_g = U_{g\text{-}0} + \int_0^t (\dot{m}_{in\text{-}g} h_{in\text{-}g} - \dot{m}_{out\text{-}g} h_{out\text{-}g})dt + \int_0^t \left(\sum_k (Q_{w\text{-}g})_k\right)dt - \int_0^t \left(\sum_k \alpha_k \omega_k \tau_k\right)dt$$
$$- \int_0^t \left(\sum_k (P d\alpha_g/dt)_k\right)dt + \int_0^t \left(\sum_k (H_{ig}(T_s - T_g)V)_k\right)dt + \int_0^t \left(\sum_k (h_g \Gamma_i + h_g \Gamma_w + h_f \Gamma_c)_k\right)dt ,$$ (8)

where h_g and h_f are the enthalpies of the gas and liquid phases, P is the pressure, H_{ig} is the heat transfer coefficient between the interface and the vapor times the interfacial area per unit volume, T_s and T_g are the saturation and gas temperatures, Γ_i, Γ_w, and Γ_c represent the interfacial mass transfer per unit volume at the interface, due to boiling at the wall, and due to condensation at the wall, respectively. Equation 8 neglects the terms associated with viscous dissipation and interfacial heat transfer in the presence of noncondensables. In the code, the phasic enthalpies are evaluated at either bulk or saturation conditions, depending on the process. For simplicity, the phasic enthalpies are all based on bulk fluid properties in the current analysis. The interfacial mass transfer terms are related by

$$\Gamma = \Gamma_i + \Gamma_w + \Gamma_c . \tag{9}$$

The global gas energy balance obtained by RELAP5-3D can be checked by comparing the right hand sides of Equations 7 and 8.

The basic variables used in Equations 1 through 8 are all based on minor edit variables that are readily available in the code. Control variables are used to calculate the terms in the equations.

3.0 Results

The reactor model selected for this analysis is based on an installation problem that is provided with the code, typ12002.i. This input model simulates a SBLOCA in a typical pressurized water reactor (PWR). The SBLOCA is initiated by a 4-inch diameter break in the cold leg. The primary coolant system was selected for detailed analysis. The nodalization for this model is shown in Figure 1.
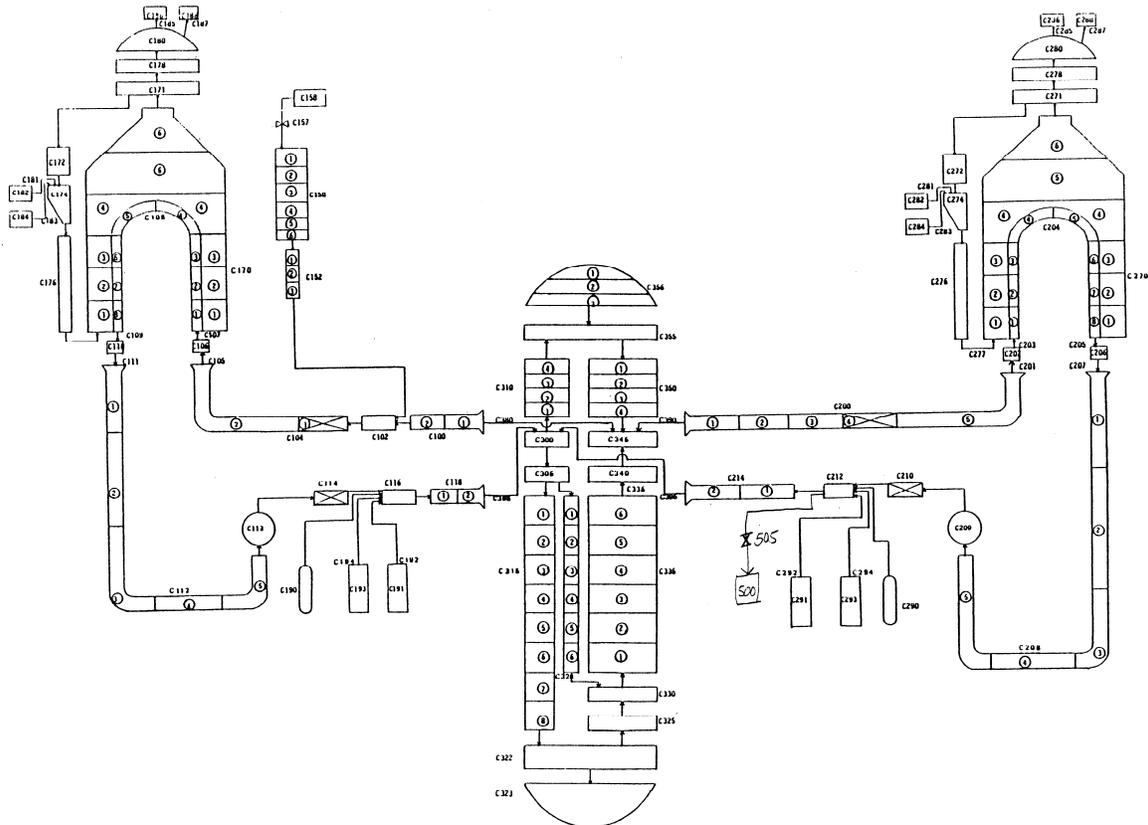

Figure 1. Nodalization diagram for the typical PWR model.

The inflows from the primary coolant system were due to the flow from the high-pressure injection and charging systems, which were modeled with time-dependent volumes and junctions. The only outflow from the system was from the cold leg break. The accumulators were treated as normal control volumes within the primary coolant system. The $H_{ig} (T_s - T_g)V$ term in Equation 8 was replaced by $-H_{gf}(T_g - T_f)V$ for the accumulators to account for the direct heating term that dominates the interfacial heat transfer when the partial pressure of steam is low (see

Equation 3.1-84 of Volume 1 of the manual). H_{gf} is the direct heating heat transfer coefficient times the interfacial area per unit volume. The H_{gf} minor edit variable is set to a default value, rather than the value internally used by the code, for accumulator components and is not accurate. Consequently, a representative value was used in this analysis.

The results of the mass balances are shown in Figures 2 and 3. The first curve in each figure represents the value obtained by integrating the conservation equation. The second curve represents the values obtained by summing the mass for each control volume in the primary coolant system. RELAP5-3D adequately conserved the total mass of the fluid and the gas. The difference between the total mass calculated by Equations 1 and 2 was 0.04% at 1200 s. The difference between the gas mass calculated by Equations 3 and 4 was 0.3%.
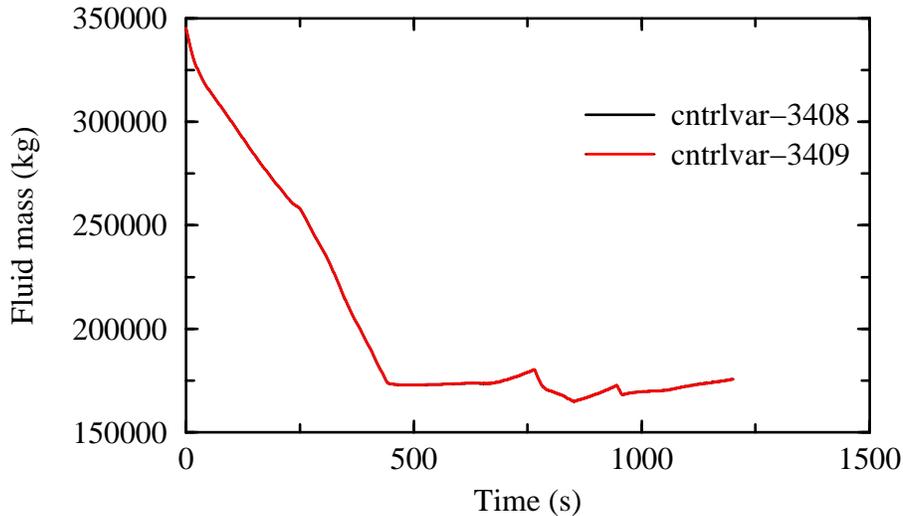

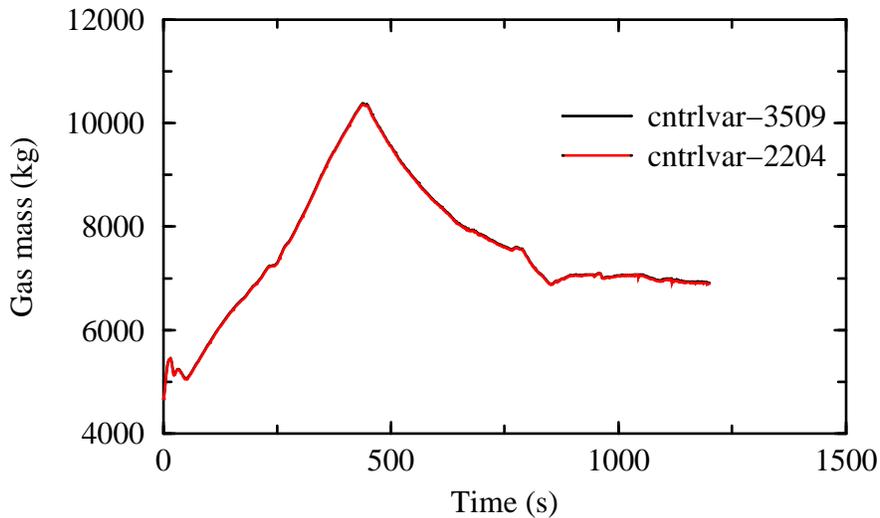Figure 2. Total fluid mass in the primary coolant system.

Figure 3. Total gas mass in the primary coolant system.

The results of the energy balances are shown in Figure 4 for the total fluid and Figure 5 for the gas. The difference between the total energy calculated by Equations 5 and 6 was 1.2% at 1200 s.

The difference between the total gas energy calculated by Equations 7 and 8 was 1.0% at 1200 s. Because of the simplifications involved in the energy balances, the differences were expected to be larger than those obtained for mass. However, the magnitudes of the differences are still small, which indicates that the code adequately conserved the total energy of the combined fluid and the gas.
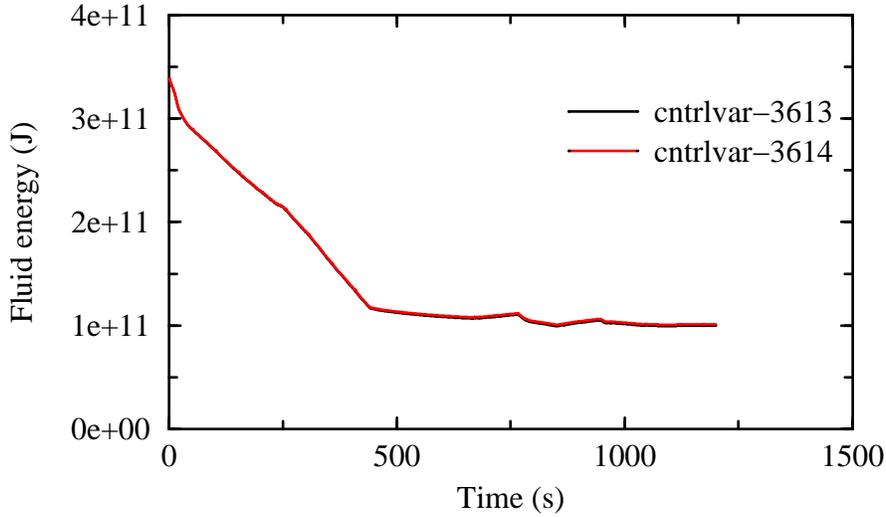

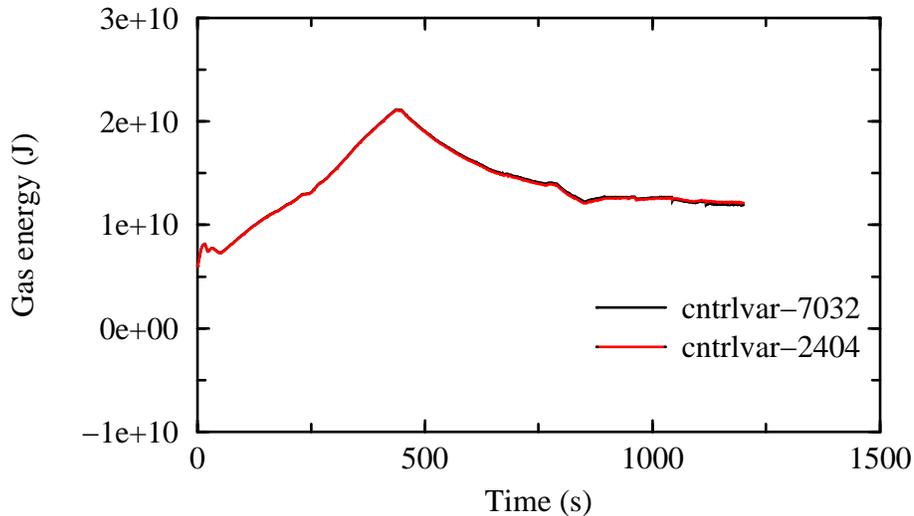Figure 4. Total fluid energy in the primary coolant system.

Figure 5. Total gas energy in the primary coolant system.

The typical PWR model represents the primary coolant system with 107 control volumes. The mass and energy balances described in Equations 1 through 8 used 2034 control variables, roughly 20 control variables per volume.

4.0 Conclusions

RELAP5-3D adequately conserved mass and energy during a SBLOCA in the typical PWR model for both the combined fluid and the gas phase. Consequently, the code also adequately conserved the mass and energy of the liquid phase. The accuracy of the solution for the gas phase was similar to that for the combined fluid.

5.0 References

1. RELAP5 Development Team, RELAP5-3D Code Manual, Code Structure, System Models, and Solution Methods, Volume 1, Revision 2.4, INEL-EXT-98-00834, June 2005.

6.0 Acknowledgment