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EFFECTS OF STATE PROPERTIES ON HIGH PRESSURE COMPRESSIBLE HYDRODYNAMICS

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ABSTRACT

As part of a continuing effort in the development of computer codes for reactor safety analysis, the ASME equations of state for water have been incorporated into RELAP3 as a trial version called RELAP3/ASME. In comparisons to the experimental data from Semiscale Test 820-1, this trial version gives substantial improvement over RELAP3 in predicting subcooled blowdown pressure histories.

The standard version of RELAP3 is a computer code for analyzing reactor core and loop thermal hydraulics during blowdown. Continuous calculations from the subcooled portion of the blowdown into the two-phase regime are at least conceptually permitted. The failure of RELAP3 to correctly predict subcooled pressure histories was traced to inaccurate sonic velocities. Water properties are built-in as tables of pressure versus enthalpy and density. Thermodynamic derivative quantities, such as sonic velocity, are implicit within these tables.

These tables and any dependence on interpolation schemes were eliminated in RELAP3/ASME by incorporating the 1967 ASME equations of state. Each equation, which is defined for particular ranges of pressure and temperature, uses either pressure and temperature or specific volume and temperature as independent variables. Within RELAP3/ASME, a two-dimensional Taylor series expansion is performed on the ASME equations which transforms the independent variables to specific internal energy and specific volume. This complex transformation is performed many times for each volume during a transient calculation and therefore is not efficient with respect to computer time. Current work is directed at making an efficient production code by developing tables of Taylor coefficients that can be used as explicit equations of state. These techniques and subroutines will need only slight modifications for any choice of independent thermodynamic variables.

INTRODUCTION

As part of a continuing effort in the development of computer codes for reactor safety analysis, the 1967 ASME equations of state for water were incorporated on a trial basis into the RELAP3 code^[1,2]. The major purpose of this trial version was to investigate, qualitatively, how another computer form of state properties affects blowdown calculation.

The results reported here are based on this trial version of the RELAP3 code called RELAP3/ASME. No effort was made to make RELAP3/ASME an efficient production tool and in fact, its only purpose was for this study.

Previous experience with blowdown codes using the nodal volume concept showed deficiency in their ability to predict subcooled decompression to an acceptable accuracy. Although the current physical models and solution techniques used in RELAP3 can and will be improved in future generations of the code, our main concern herein is to determine what form of state properties is necessary for future blowdown codes.

EXPERIMENTAL WORK

Considerable experimental blowdown data exists from the Semiscale series of tests produced by Idaho Nuclear Corporation^[3]. This test rig is a small scale mock-up of a pressurized water reactor hydraulic system. The major components are the reactor vessel, steam generator, and primary coolant pump. The general layout of these components and interconnecting piping is shown in Figure 1.

Test 820-1 was chosen as the experimental base for several reasons: an uncluttered one-dimensional geometry existed from the auxiliary nozzle through the steam generator (Figure 1); the greatest pressure transients occurred during this test in comparison to other semiscale tests; and the simulated offset shear break presents the greatest probability of significant two-phase conditions behind the initial decompression wave.

Test 820-1 used two blowdown nozzle assemblies to simulate a double-ended break. Simultaneous 100% pipe area break capability was designed for both nozzles as shown in Figure 1. A crossover pipe connecting the two blowdown pipes allowed some minor flow prior to blowdown for developing the desired isothermal temperature distribution throughout the system. A valve in the crossover pipe was closed just prior to initiation of the blowdown.

Initial conditions for Test 820-1 were a temperature of 588°F, a pressure of 2263 psia, and no system flow. The breaks were sized at 100% of the 0.09 ft² blowdown pipe areas for a double-ended-break blowdown having a total break area of 0.18 ft².

The method of rupture initiation for Semiscale Test 820-1 was underpressurization of the space between two rupture disks located in the blowdown nozzle assembly. For this method, the upstream disk ruptures first and starts a decompression into the system. At this time a pressure wave is moving out of the system and hits the downstream disk, starting a compression wave into the system. About 1 msec later the downstream disk ruptures and starts a second decompression wave into the system. Thus, the initial primary decompression process is composed of two parts that are dependent on the individual disk characteristics^[4].

The decompression wave traveling into this system from the auxiliary nozzle is relatively simple although the acoustical reflections from the steam generator (24 feet from the auxiliary nozzle) produce a complex pressure transient. As shown in Figure 2, the experimental pressure record of P5 (which is located 1.07 ft below the steam generator) begins to fall at 8 milliseconds which is the pressure wave propagation time for 24 feet at 3000 ft/sec. Between 8 and 10 milliseconds, several minor pressure fluctuations are superimposed on the general decompressions. These are attributed to the two-part primary decompression wave generated by the rupture device and to reflections from the tubes within the steam generator. The pressure rise, which begins at 12 milliseconds, is attributed to the reflection from the upper plenum of the steam generator.

RELAP3

RELAP3 is a multivolume compressible hydrodynamics and heat transfer code designed to analyze the transient phenomena of a reactor blowdown. In RELAP3, pressures, flows, temperatures, and other hydraulic related quantities are calculated as averages over mathematical control volumes. The choice of volume size is entirely a user option. To simulate Test 820-1 with a minimum of extraneous complications such as the stability associated with unequal volume sizes, the piping from the auxiliary nozzle to a location beyond P6 was divided into 69 volumes each one-half foot long.

Figure 3 is the pressure history for location P5 as calculated from the published version of RELAP3. In general, the results are unacceptable. The arrival time of the decompression wave is about 2 milliseconds early, which suggests an erroneous sonic velocity. Further transient detail has at best only a passing resemblance to the experimental pressure trace of P5. Plots of other RELAP3 volume pressures gave a hint that the major error might be due to the steam tables contained within the code.

Water properties are contained within RELAP3 as tables of pressure vs. enthalpy and density. In general, these tables are constructed at 24 different pressures from .1 psia to 3200 psia and at each pressure there are 13 entries of density and enthalpy for the liquid region and five additional entries for the super heat region to 5600°F.

Sonic velocity, which thermodynamically is defined as $\sqrt{\left(\frac{\partial p}{\partial \rho}\right)_s}$ for single phase fluids, is contained implicitly within the tables. In the pressure range of interest for this problem, the tables are spaced at even increments: 1200, 1400, 1600, 1800 ... 2400 psia. Since the interpolation technique involves a double-linear interpolation, first on pressure, then on density and enthalpy, the sonic velocity produced by these tables can change discontinuously across pressure entry points as shown in Figure 4. The curve labeled RELAP3 is density vs. pressure for a constant internal energy as determined from the water property tables. The curve labeled ASME is density vs. pressure for a constant temperature as computed from the ASME equations. The slope of the ASME curve is smoothly varying as contrasted to the discontinuities in the slope of the RELAP3 curve.

This resulting discontinuity in sonic velocity with RELAP3 was thought to be the cause of the false pressure reflections during a calculated transient. To test this idea, the ASME equations were adapted to RELAP3.

RELAP3/ASME

The combination of RELAP3 and the ASME equations, named RELAP3/ASME formed an inefficient long-running code which was useful only for these calculations. Within RELAP3/ASME, a two-dimensional Taylor series expansion is performed on the ASME equations which transforms the independent variables to specific internal energy and specific volume. This transformation is performed many times for each volume during a transient calculation and therefore is very inefficient with respect to computer time. Previous work with the ASME equations showed that the derivatives were smooth and continuous to a very high degree except at boundaries where the form of the ASME equations change from a Gibbs function to a Helmholtz function. These narrow discontinuities occur at 2398.2 psia and hence have no effect on calculations for Test 820-1.

Figure 5 is the pressure history of P5 as calculated by RELAP3/ASME and Figure 6 is an overlay of this calculated curve and the experimental pressure trace. The

agreement is much superior in comparison to the RELAP3 calculation. The initial decompression wave at P5 is calculated to occur within .5 milliseconds of the experimental value and the first reflection from the steam generator starts 1.5 milliseconds later, which is the round-trip time from P5 to the steam generator. Approximately 3.5 milliseconds after the first decompression wave passes P5, the broad recompression wave, which is reflected from the steam generator upper plenum arrives at P5. Qualitatively, this slope agrees with the experimental trace. The high frequency oscillation superimposed on the calculated pressure is due to an instability associated with the volume size in the RELAP3/ASME calculations.

CONCLUSIONS

Since the only change between RELAP3 and RELAP3/ASME was in the state property formulations, the calculated differences between these codes is due to the inaccuracies in the standard RELAP3 state properties and the equivalent derivatives. Subsequent work not reported here has shown that this type of error is also present in two-phase transients as well as the subcooled phase although the errors are not nearly so pronounced.

Our conclusions are that transient hydraulic codes intended for compressible fluid dynamic analysis must contain reasonably accurate state properties including smoothly varying derivatives of the state properties.

CURRENT WORK

A state property package based on sets of Taylor coefficients is currently being developed, and the user will have a limited choice of independent thermodynamic variables. Current designs include specific energy and specific volume (u, v), pressure and internal energy (P, u), and enthalpy and specific volume (h, v). This package is complete for the two-phase region and is nearing completion for the single-phase regions. As designed, this package is an independent module for general use. The execution rate is approximately 10,000 independent state solutions per 1.5 minutes of 360/75 CPU time. This speed is comparable to the published RELAP3 code and considerably faster (by several orders of magnitude) than RELAP3/ASME.

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ROUGH DRAFT

INC-8-13037

Fig.-5 Single-loop semiscale double-ended-break configuration.

Figure 5

ROUGH DRAFT

H. D. Curet
KVM-7-70
Attachment, Page 4

FIG. 2-4 TEST 8201 P-5 2/2/70

ROUGH DRAFT

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Attachment, Page 1

R3/B-RQ534-3/19/70-GEG-SUBCOOL. STUDY OF TEST B20-1 HT EXCHGR

RELAP3

AVG. PRESS. PSIA N
2800
2400
2000
1600
1200
800
400

ROUGH DRAFT

H. D. Curet
KVM-7-70
Attachment, Page 1

RELAP3

AVG. PRESS. PSIA N 2400 2000 1600 1200 800 400 000

000.000 200.000 400.000 600.000 800.000 1000.000 1200.000 1400.000 1600.000 1800.000 2000.000 2200.000 2400.000 2600.000 2800.000 3000.000 3200.000 3400.000 3600.000 3800.000 4000.000 4200.000 4400.000 4600.000 4800.000 5000.000 5200.000 5400.000 5600.000 5800.000 6000.000 6200.000 6400.000 6600.000 6800.000 7000.000 7200.000 7400.000 7600.000 7800.000 8000.000 8200.000 8400.000 8600.000 8800.000 9000.000 9200.000 9400.000 9600.000 9800.000 10000.000

TIME SEC.

2

ROUGH DRAFT

(8, 7, 2)

(8, 5, 0)

10 x 25 CM.
KEUFFEL & ESSER CO.

4415

4414

4413

4412

4411

4410

4409

4408

4407

2

ROUGH DRAFT

H. D. Curet
KVM-7-70
Attachment, Page 3

R3/ASME-RQS34-8/11/70-GEG-SUBCOOL STUDY OF TEST 820-1 HT EXCHGR

RELAP3/ASME

100

ROUGH DRAFT

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KVM-7-70
Attachment, Page 3

RELAP3/ASME

TIME SFC
000 002 004 006 008 010 012 014 016 018 020

2

ROUGH DRAFT

Figure 6