RELAP5 ASSESSMENT OF NONCONDENSABLE TEST DATA FOR PASSIVE COOLING APPLICATIONS

Craig Kullberg
Idaho National Engineering Laboratory,[a]
EG&G Idaho, Inc.
Nuclear Reactor Research and Technology, MS 2403
Idaho Falls, Idaho 83415
(208) 526-9565

ABSTRACT

Condensation heat transfer in the presence of noncondensable (NC) gases is of concern in the design of passive heat removal systems for a number of recently proposed advanced reactor designs. In general, the presence of NCs will degrade the efficiency of such passive heat removal systems and, in some cases, induce unstable flow patterns. As part of a research effort to better understand passive heat removal dynamics, a series of numerical steady-state simulations in the presence of NCs were performed to evaluate RELAP5/MOD3 against test data. This assessment was made using data from the University of California, Berkeley (UCB) natural circulation loop test facility. For fine enough nodalization in the condenser region, the RELAP5/MOD3 simulations generally captured the same phenomena as observed in the tests.

INTRODUCTION

In future reactor designs, passive energy removal schemes driven by natural circulation will be one of the principal means of removing reactor decay energy following a loss of coolant accident (LOCA). This paper presents RELAP5/MOD3 code assessment work that has been used to support the Nuclear Regulatory Commission's (NRC) evaluation of General Electric's Simplified Boiling Water Reactor (SBWR). The SBWR is an advanced design which relies on a passive containment cooling system (PCCS) for long term cooling of containment. The PCCS heat exchangers remove core decay power by free convection and transfer this energy to an external pool of water located above containment. To make reliable design decisions about PCCS operation, basic questions must be answered as to how steam/NC mixtures will transfer energy to their surroundings. Several relevant experimental or theoretical investigations have been conducted in the last several years to provide improved heat transfer correlations for steam in the presence of NC gases.[1,2,3] In particular, a series of tests for natural circulation, NC heat transfer test facility have been done at the UCB. One of the key objectives of the UCB program was to observe steady-state operation to simulate energy removal for proposed PCCS designs. The UCB facility simulated expected containment accident conditions with pressures that ranged from 1 to approximately 4 atmospheres. These tests were used to quantify the inhibitive effect of NCs on steam condensation heat transfer. This test data was used to assess the capability of RELAP5 to simulate condensation heat transfer in the presence of NCs.

The need to quantify NC heat transfer during post-LOCA conditions becomes obvious when attempting to design passive core decay energy removal systems. During a LOCA, a mixture of steam and air is convected to the PCCS inlet located at the top of the dry well. Once natural circulation is established in the PCCS, condensate is returned to a raised tank in containment for ultimate recirculation back to the reactor core. Natural circulation in the PCCS is driven by film condensation inside the PCCS condenser tube walls. The degree of core decay power removal is determined by the local tube wall heat transfer rate and net differential buoyancy forces between the PCCS inlet and outlet.

TEST DESCRIPTION AND RELAP5 MODEL

The base case RELAP5/MOD3 nodalization model for the UCB experimental natural circulation loop is shown in Figure 1.[b] The NC loop consists of a lower plenum tank into which steam and NCs are injected. The lower plenum also serves as a return path for condensate exiting from the NC loop outlet. The vertical riser section and shorter U-bend down section are 51 mm diameter pipes that transports a steam air/mixture to the condenser section. The single vertical condenser tube section is a 25.4 mm, 2.1 m long section connected to 12.7 mm condensate plenum return line. Piping outside of the condenser region was insulated to minimize environmental heat losses. The secondary side of the condenser was an annular water cooling jacket. Secondary side cooling was single phase liquid and was maintained to induce complete condensation on the primary side of the natural circulation loop. Steam supplied to the loop allowed up to 19 kW of energy to be removed by the condenser section.

[a] This work was supported by the U.S. Nuclear Regulatory Commission, Office of Research, under DOE Contract No. DE-AC07-76ID01570.

[b] This model is based on the original UCB facility configuration that ran tests with steam/air mixtures. More recent configurations have slightly different dimensions and have been used to perform tests with other kinds of NCs.

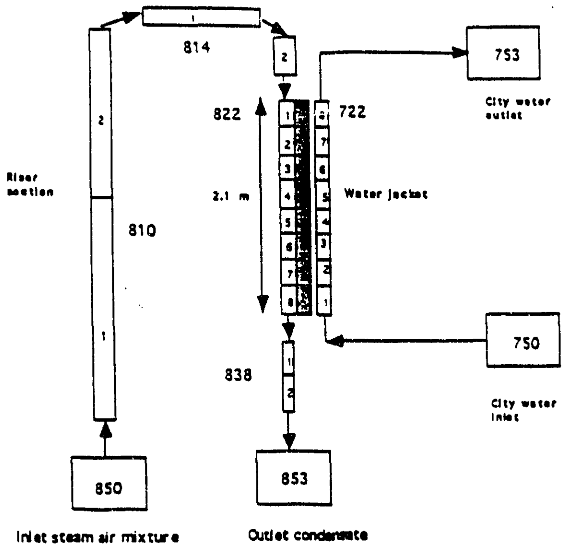

Figure 1 - UCB base case RELAP5 nodalization.

Instrumentation in the loop consisted of thermocouples, flow meters, and pressure transducers which supplied inputs to a data reduction program that estimated local heat transfer rates along the length of the condenser test section. Additional details about instrumentation as well as auxiliary support systems such as heaters and vacuum pumps for generating steam, and controlling NC gas fractions are detailed in Reference 1.

The base case, natural circulation loop, RELAP5 model consisted of 26 volumes, 16 junctions, and 8 heat structures. Volume regions outside of the condenser region were assumed to be adiabatic. The lower plenum was modeled as a time dependent constant pressure boundary condition. The inlet boundary conditions for pressures and NC mass fractions were matched to those estimated in the lower plenum test section. The inlet conditions were assumed to be at 100% humidity. All volumes were modeled with multi-phase nonequilibrium modeling options. In the present RELAP5/MOD3 field equations, the vapor and NCs are locked together and are assumed to be in temperature equilibrium.

RESULTS AND DISCUSSIONS

Table 1 presents an overall comparison of the energetics for measured and calculated condenser energy removal rates for a range of pressures and NC gas fractions. In these simulations 16 nodes were used in the condenser tube region. Results from the base case model which used 8 nodes were judged to be inadequate. In general, given the same local NC mass fraction, the measured local heat transfer coefficients exceeded the calculation and the measured condensation length was less than the calculated. The condensation length is characterized by that region of the condenser where there was significant condensation heat transfer. Outside of this region heat transfer is extremely small. To illustrate the above differences, Figures 2 and 3 present comparisons for local heat transfer coefficients for

Table 1 - UCB/RELAP5 Comparisons of Condenser Energy Removal Rates.

Test	Inlet saturation pressure(MPa)	Inlet NC fraction	Measured removal rate(kW)	Calculated power removal rate(kW)
9	0.17	0.042	5.19	4.90
11	0.21	0.11	4.76	5.03
13	0.18	0.13	4.99	4.10
19	0.30	0.11	6.93	7.13
20	0.24	0.14	4.48	5.25
26	0.37	0.08	10.93	9.39
36	0.42	0.045	17.18	11.48

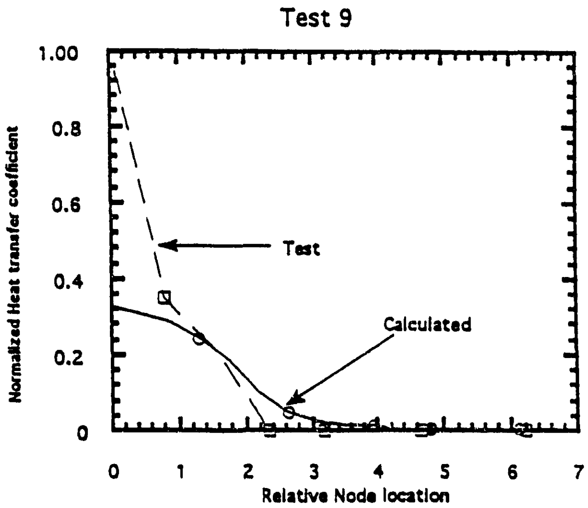

Figure 2 - Measured and calculated heat transfer coefficients.

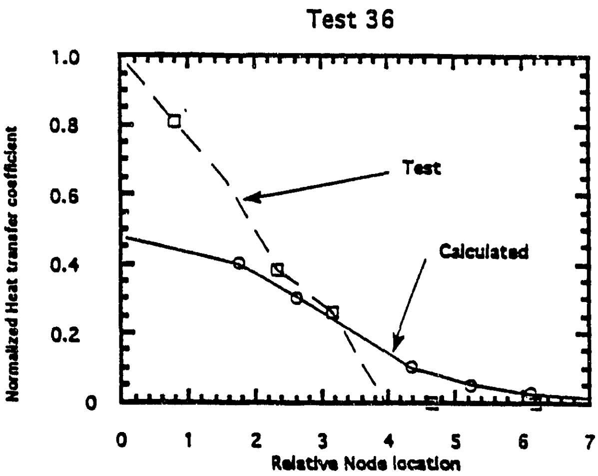

Figure 3 - Measured and calculated heat transfer coefficients.

test runs 9 and 36, respectively. These two compensating effects (underpredicted local heat transfer coefficients and over predicted condensation lengths) resulted in some measured energy rates exceeding the calculated values while in other tests the opposite situation prevailed. A better insight in these differences is gained by analyzing the local heat transfer dynamics during this condensation process.

In both the experiments and simulations, the heat transfer regime was characterized by laminar film condensation. The corresponding heat transfer coefficients can be quantified using the standard laminar Nusselt film condensation correlation multiplied by a correction or degradation factor to account for the presence of NCs. In the test data the film Reynolds numbers were less than 600 which justified the use of laminar theory. With regard to the RELAP5 simulations, the calculated liquid film Reynolds numbers were generally less than 1000. Using regression analysis on the UCB data, a NC correction factor correlation was expressed with the following relationship:

$$h_{NC} = 0.0050\ Re_f^{.45}\ M_a^{-1.1}\ h_{Nusselt} \qquad (1)$$

Where h_{NC} is the measured heat transfer coefficient, $h_{Nusselt}$ is the theoretical laminar heat transfer coefficient in the absence of NCs, so that $h_{NC}/h_{Nusselt}$ is defined as the correction factor, M_a is the local NC mass fraction in the range $1.0<M_a<.05$, and Re_f is the film Reynolds number in the range $50<Re_f<600$. The above correction factor had an uncertainty of 30%. The corresponding RELAP5 correction factor was formulated using the relationships:

$$h_{NC} = F[Re_g, M_a]\ h_{Nusselt} \qquad (2)$$

$$F[Re_g, Ma] = (1 - M_a)/(1 + f[Re_g]) \qquad (3)$$

$$f[Re_g] = 5./(1 + .0001\ Re_g) \qquad (4)$$

Where Re_g is the gas Reynolds number such that $0<Re_g<20000$, and $1.0<M_a<.0001$[4]. The expression $F[Re_g, Ma]$ is the actual correction factor. In Equation 3 there is also a weak dependence on wall sub-cooling that is not shown. For the range of subcooling conditions in the simulation this effect was not important. In the RELAP5 simulations, the calculated gas Reynolds numbers ranged from 1 to 10 times the value of the corresponding liquid Reynolds numbers. Presented in Figure 4 are ratios of the degradation factors given by Equations 1 and 2. In this example, the film Reynolds number was held at 500 and the gas Reynolds number was varied from 500 to 5000. These values were in the range of Reynolds numbers observed in both the test and simulations. From these comparisons it is clear that the empirical correction factor is consistently greater than that calculated for RELAP5. The largest differences between the RELAP5 and experimental models are at either high or low local NC gas fractions. In test 36 there was an extended region in the condensation zone where the local NC mass fraction was relatively low in comparison to other tests shown in Table 1. Consequently, the predicted net energy removal rate for test 36 RELAP5 stood out as being the most underpredicted case.

Explanations as to why condensation lengths were over predicted are more difficult to discern. More accurate heat transfer correlations are expected to reduce calculated

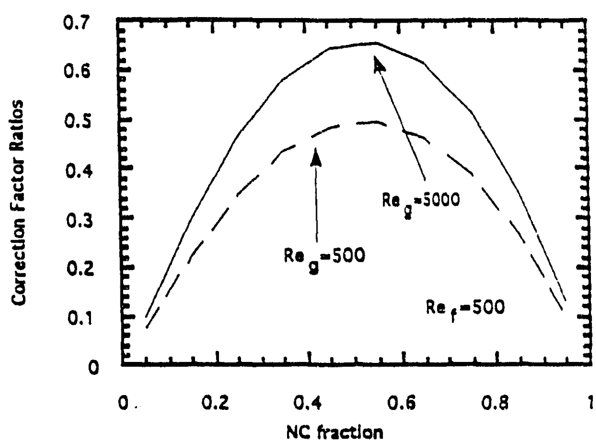

Figure 4 - RELAP5 to UCB correction factor ratios for constant Reynolds number.

condensation lengths because of the attendant reduction in the vapor mass fraction down stream of the condenser inlet. However, nodalization densities in the condenser tube region and associated numerical diffusion may also play a major role in the predicted condensation length size. Sensitivity studies indicated that coarse nodalization (less than 8 nodes) in the condenser region tends to significantly reduce the total calculated energy removal rate and also tends to artificially extend the effective condensation length.

CONCLUSIONS

Use of RELAP5/MOD3 to simulate condensation heat transfer in the presence of NCs indicated that in general for the same local conditions the local heat transfer coefficient was underpredicted. On the other hand, calculated condensation lengths were generally larger relative to the test data. These two compensating effects resulted in net calculated heat transfer rates fluctuating about the experimental results. The character of the calculated condensation length was dictated not only by the local heat transfer correlation, but also by the model nodalization density. Generally, higher nodalization densities produced calculated results that were in better agreement with data. Future versions of RELAP5 will require updated correlations to better predict condensation heat transfer in the presence of NCs.

NOTICE

REFERENCES

1. K. M. VIEROW, Behavior of Steam-Air Systems Condensing in Cocurrent Vertical Down Flow, MS Thesis, University of California, Berkeley (1990)

2. M. SIDDIQUE, M. W. GOLAY, M. S. KAZIMI, "Local Condensation Heat Transfer Coefficient for Internally Flowing Steam/Air Mixtures," Proc. 7th Nucl. Thermal Hydraulics Conf., San Francisco, California, November 10-14, 1991, American Nuclear Society (1991).

3. A. A. DEHBI, M. W. GOLAY, M. S. KAZIMI, "Model of Condensation in Stagnant Steam-Noncondensable Gas Mixtures," Proc. 7th Nucl. Thermal Hydraulics Conf., San Francisco, California, November 10-14,1991, American Nuclear Society (1991).

4. K.E. CARLSON et. al., RELAP5/MOD3 Code Manual Volume IV, NUREG/CR-5535, EGG-2596, June 1990.

DATE FILMED

1 / 10 / 93