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Thermal-Hydraulic Simulation of Natural Convection Decay Heat Removal in the High Flux Isotope Reactor (HFIR) Using RELAP5 and TEMPEST

Part 2: Interpretation and Validation of Results

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Thermal-Hydraulic Simulation of Natural Convection Decay Heat Removal in the High Flux Isotope Reactor (HFIR) Using RELAP5 and TEMPEST

Part 2: Interpretation and Validation of Results

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1. INTRODUCTION

The RELAP5/MOD2 code was used to predict the thermal-hydraulic behavior of the HFIR core during decay heat removal through boiling natural circulation. The low system pressure (i.e., 22 psia) and low mass flux values associated with boiling natural circulation are far from conditions for which RELAP5 is well exercised. Therefore, some simple hand calculations are used herein to establish the physics of the results.

The interpretation and validation effort is divided between the time average flow conditions and the time varying flow conditions. The time average flow conditions are evaluated using a lumped parameter model and heat balance. The Martinelli-Nelson correlations are used to model the two-phase pressure drop and void fraction vs flow quality relationship within the core region.

Systems of parallel channels are susceptable to both density wave oscillations and pressure drop oscillations. Periodic variations in the mass flux and exit flow quality of individual core channels are predicted by RELAP5. These oscillations are consistent with those observed experimentally and are of the density wave type. The impact of the time varying flow properties on local wall superheat is bounded herein.

The conditions necessary for Ledinegg flow excursions are identified. These conditions do not fall within the envelope of decay heat levels relevant to HFIR in boiling natural circulation (i.e., $q_c < 1 \times 10^6$ Btu/h).

2. TIME AVERAGE FLOW CONDITIONS

A lumped parameter model is presented in Figure 1 that captures the physics of the HFIR boiling natural circulation loop. It is assumed that the heat input to the core region is rejected in the upper plenum such that the average loop temperature is constant. Dimensions for each part of the system model are listed in Table 1.

TABLE 1: HYDRAULIC DATA

	D_h(FT)	L(FT)	A(FT^2)
Core	0.008	1.9	0.54
Upper Flow Annulus	0.5	4.0	1.2

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†Operated by Martin Marietta Energy Systems, Inc. under contract No. DE-AC05-84OR21400 with the U.S. Department of Energy.

The pressure drop in the core is evaluated using the Martinelli-Nelson, 1948, friction multiplier and void fraction vs flow quality relationships. The Martinelli-Nelson correlations were developed from data taken in horizontal pipes. Thus, they can be expected to overpredict interphase slip and will underpredict the local void fraction at given mass and heat flux values. The core inlet and exit losses are negligible.

The downcomer (i.e., target region) is single phase and has a very complicated flow geometry. Therefore, the pressure drop in the downcomer is modeled by scaling pressure drop data taken for higher flow conditions. The pressure drop during normal operation is known to be 105 psi when the volume flux is 750 gal/min. Assuming the pressure drop goes as the flow velocity squared, the target pressure drop is given generally as,

1a) $$\Delta p_t = C_T A_C^2 G^2 - g\rho_L L_T \quad \frac{\mathrm{Lb_f}}{\mathrm{ft^2}} \quad ,$$

where

1b) $$C_T = 1.55 \quad \frac{\mathrm{Lb_f} - \mathrm{s}^2}{\mathrm{Lb_m} - \mathrm{ft}^2} \quad .$$

The pressure loss in the flow annulus above the core is very small. However, significant bouyancy head is contributed by this region. The void fraction in the upper flow annulus is calculated assuming a constant drift velocity (Lahey and Moody, 1977),

2) $$V_{jG} = 2.9 \left[\frac{(\rho_L - \rho_G)\,\sigma g g_c}{\rho_L^2}\right]^{1/4} \quad .$$

The void fraction follows from the Zuber-Findlay, 1965, void-quality model given as,

3) $$\alpha_A = \frac{x}{C_o\left[x + \frac{\rho_G}{\rho_L}(1 - x)\right] + \frac{\rho_g V_{jG}}{G}} \quad ,$$

where the concentration parameter, C_o, is taken as unity.

The mass flux in the loop can now be written in terms of the core exit flow quality as,

4a) $$G = \left\{\frac{g\left[\int_o^{L_c} (\alpha_C\rho_L - \alpha_C\rho_G)\,dz + \alpha_A L_A (\rho_L - \rho_G)\right]}{\frac{2\,C_{L_o} L_C}{D_h\rho_L}\,\bar{\phi}_{L_o}^2 + r_2 + C_T A_C^2}\right\}^{1/2} \quad ,$$

where

4b) $$r_2 = \frac{1}{\rho_L}\left[\frac{x^2\rho_L}{\alpha\rho_G} + \frac{(1 - x)^2}{1 - \alpha} - 1\right] \quad .$$

The two-phase friction multiplier, $\bar{\phi}_{L_o}^2$, is taken from Martinelli-Nelson and the single phase drag coefficient, C_{L_o}, is taken as 0.013 from HFIR flow data. The core mass flux and exit flow quality is related to the decay heat level by,

$$5)\qquad q_c = h_{LG} G A_C x_{C,E}$$

where saturated inlet conditions have been assumed.

Figure 2 shows the variation of core mass flux with core decay heat level as predicted by the Martinelli-Nelson flow model. Figure 3 shows the variation of the core exit flow quality with decay heat level. The core exit void fraction is also shown in Figure 3. Notice that the core exit void fraction is in excess of 80% for core exit flow qualities in excess of ten percent. The steady state mass flux values predicted by RELAP5 are consistent with those predicted by the Martinelli-Nelson model as evidenced by the comparison points included in Figure 2.

3. DENSITY WAVE OSCILLATIONS

Density wave oscillations have been observed in a number of boiling forced and natural circulation experiments (Mishima and Nishihara, 1987, 1985; Mishima et al., 1985; Gambill, 1968; Gurgenci et al., 1983; Lottes et al., 1958). Of these, the experiments of Mishima and Nishihara and of Gambill involved narrow rectangular channels.

Ishii and Zuber, 1970, developed a simple expression for the region where density waves can be expected,

$$6)\qquad x_{C,E} > \left[\frac{4D_{L_o}\bar{\phi}_{L_o}^2 \rho_G}{D_h}\right] \left[1 + \frac{C_{L_o}\bar{\phi}_{L_o}^2}{D_h}\right]^{-1} (\rho_L - \rho_G)^{-1} \quad .$$

Equation 6 indicates that density waves will exist in the HFIR core whenever the exit flow quality exceeds one percent.

Stenning, 1964, found that the period of a density wave, τ, should be approximately equal to the mass transport time. This is the case in both the experimental data and in the RELAP5 predictions for HFIR. In fact, RELAP5 has successfully predicted the period and amplitude of experimentally observed density waves in a previous application (Chen et al., 1979). A typical density wave oscillation as predicted by RELAP5 for HFIR is shown in Figure 4.

The impact of the density wave on the channel thermal behavior can be assessed by considering the core fuel plate adiabatic heating rate given by,

$$7)\qquad \frac{\delta T}{\delta t} \simeq \frac{q_C}{2.3 \times 10^5} \left[\frac{h - {}^0F}{Btu - S}\right] \quad .$$

This allows the maximum amplitude of the variation in the wall superheat during the flow oscillations to be bounded by,

$$8)\qquad \Delta T_c < \frac{\delta T}{\delta t}\,\tau \quad .$$

Thus, one can assess if the channel walls will rewet after the low void fraction part of a density wave. The maximum variation in the wall superheat is given as a function of decay heat level for HFIR in Figure 5, where the mass transport time has been taken as,

$$9)\qquad \tau \simeq \frac{\rho_L(1 - \bar{\alpha}_c)L_c}{G} \quad .$$

4. LEDINEGG FLOW EXCURSIONS AND PRESSURE DROP OSCILLATIONS

The criterion for the onset of Ledinegg flow excursions in a system of parallel channels is given by,

$$10)\qquad \frac{\delta \Delta p_C}{\delta G} < 0 \quad .$$

The mass flux satisfying equation 10 for HFIR is approximately 21.5 $\mathrm{lb_m/s\text{-}ft^2}$. The corresponding decay heat level is 4×10^6 Btu/h, as taken from Figure 2. This is well above the level of decay heat that exists during boiling natural circulation in HFIR.

Pressure drop oscillations result from an interaction of the Ledinegg flow excursion with a compressible volume in the flow loop (Maulbetsch and Griffith, 1966). These oscillations usually have a longer period than the density waves. Mishima et al., 1985, observed pressure drop oscillations leading to critical heat flux in their boiling natural and forced circulation experiments.

5. CONCLUSIONS

The time averaged mass flux values predicted by RELAP are consistent with the predictions of lumped parameter system using a Martinelli-Nelson pressure drop and void fraction vs. flow quality model. The density waves predicted by RELAP5-MOD2 are in agreement with experimental observation and do not appreciably impact the average heat transfer situation in the core when decay heat levels are below 2×10^6 Btu/h. Ledinegg flow excursions are not a concern for the decay heat levels present during natural circulation.

Boiling natural and forced circulation data are needed where the entire system is characterized. Existing data are without adequate system description to allow any more than a qualitative check of the performance of the RELAP5 model. This is especially true for single channel experiments where the system stiffness, total liquid inertia, and pump characteristics play an important role in defining the response of the heated channel.

Figure 1.

HFIR NATURAL CIRCULATION LOOP

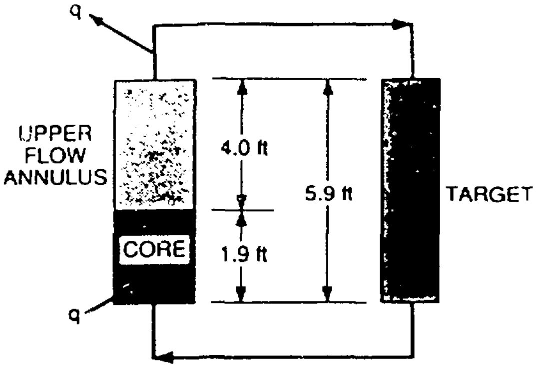


Figure 2.

CORE MASS FLUX vs CORE DECAY HEAT

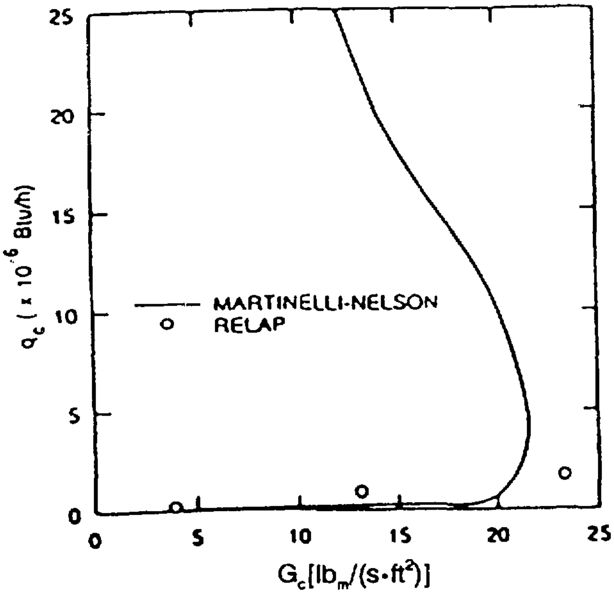


Figure 3.

CORE EXIT FLOW QUALITY vs DECAY POWER

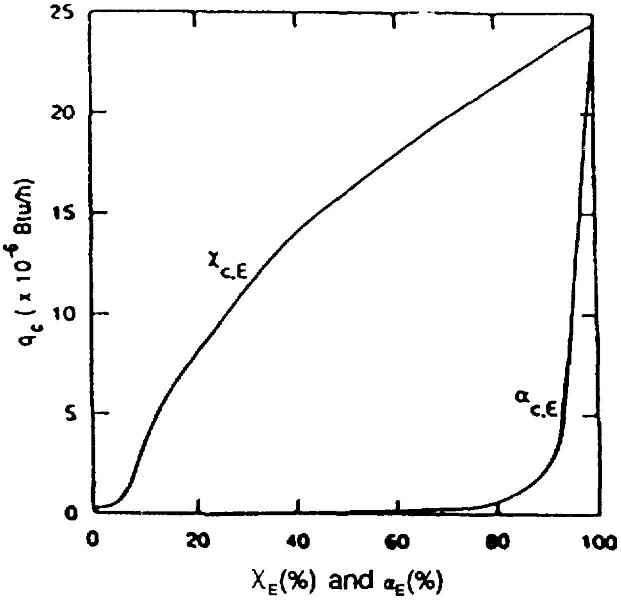


Figure 4.

CORE CHANNEL EXIT VOID FRACTION vs TIME (TYPICAL, FOR q_c=2 x 10^6 Btu/h)

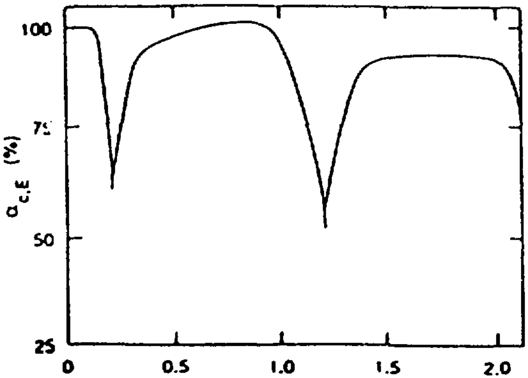
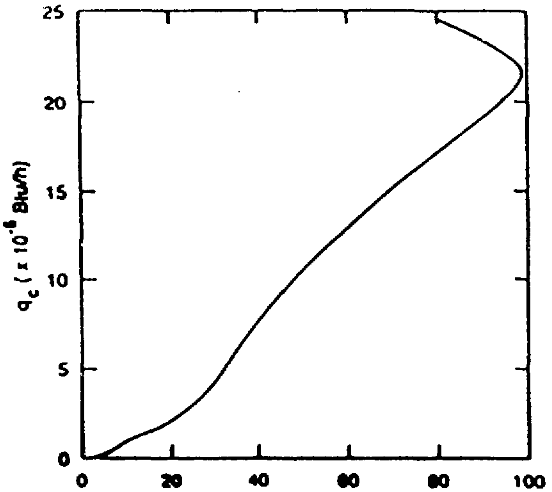


Figure 5.

MAXIMUM VARIATION IN FUEL CLAD SUPERHEAT AS A FUNCTION OF CORE DECAY POWER



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NOMENCLATURE:

SYMBOLS (ENGLISH)

A	AREA
C_{L_o}	SINGLE PHASE LIQUID DRAG COEFFICIENT
C_o	CONCENTRATION PARAMETER
D_h	HYDRAULIC DIAMETER
g	GRAVITY
G	Mass Flux
g_c	$32.17 \frac{\text{FT-LBM}}{\text{LBF}\cdot\text{SEC}^2}$
h_{LG}	ENTHALPY FOR VAPORIZATION
L	LENGTH
P	PRESSURE
r_2	ACCELERATION TERM FROM MARTINELLI-NELSON
q	POWER
t	TIME
T	TEMPERATURE
V_{jG}	DRIFT VELOCITY

(GREEK)

α	VOID FRACTION
σ	SURFACE TENSION
$\bar{\phi}^2_{L_o}$	TWO-PHASE FRICTION MULTIPLIER
ρ	DENSITY
τ	PERIOD OF OSCILLATION

SUBSCRIPTS:

A	UPPER FLOW ANNULUS
C	CORE
E	EXIT
G	GAS PHASE (VAPOR)
L	LIQUID PHASE (FLUID)
T	TARGET