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BLOWDOWN HEAT TRANSFER SURFACE IN RELAP4/MOD6

AND DATA COMPARISONS

Ralph A. Nelson
L. Harold Sullivan

EG&G Idaho, Inc.
P.O. Box 1625
Idaho Falls, Idaho 83401
United States of America

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EG&G Idaho, Inc.
Idaho Falls, Idaho U.S.A.

I. INTRODUCTION

RELAP4[1,2] is a thermal hydraulic analysis tool written to analyze transients in light water reactors (LWR). To date, most of the applications for RELAP4 have been to analyze postulated LOCA transients in LWR and the response of experimental systems to loss-of-coolant experiments. An important part of these analyses is the prediction of the fuel rod or heater surface temperature which involves the calculation of surface heat transfer coefficients. This paper describes the outcome of a significant blowdown heat transfer development effort which is incorporated in RELAP4/MOD6[2] (the current version of the code available to the United States public from the Argonne Code Center). The primary emphasis in the MOD6 development was on a PWR reflood capability[3]. The best-estimate blowdown heat transfer correlation and logic were added to provide improved blowdown predictive capability.

This discussion of RELAP4/MOD6 is limited to the best-estimate blowdown heat transfer model and evaluation of calculated results through comparison with experimental data. To develop the heat transfer model, the "boiling curve" was viewed as a function $Z = f(X_n)$ of n variables. Once the correlations and logic for the MOD6 blowdown heat transfer surface were defined, this functional concept was used to identify and eliminate discontinuities.

RELAP4/MOD6 results obtained using the blowdown heat transfer surface have been compared with Semiscale[4] and THTF[5] experiment data. Heater rod surface temperature trends were predicted and are in agreement with experimental data. These comparisons demonstrate that the developed heat transfer surface is a good representation of the rod heat transfer in these experiments.

II. HEAT FLUX VIEWED AS A MATHEMATICAL SURFACE

The function $z = f(x, y)$ may be viewed as a surface when z is plotted as a function of x and y. The understanding gained from this visual approach can be quite helpful, particularly when a number of functions $z_1, z_2, \ldots, z_N$ must be combined to cover a wide range for the independent variables x and y.

This basic approach has been used in the development of the heat transfer correlation subroutines in RELAP4/MOD6. The heat flux is viewed as a function of ΔT_{sat} (wall superheat), quality, pressure, mass flux, . . .; that is, $q = q\,(\Delta T_{sat}, X, P, G, \ldots)$. Thus, the heat flux may be considered a function of n variables. To plot the heat flux as a three-dimensional mathematical surface, the wall superheat and quality are picked as the primary independent variables, and the remaining variables are assumed constant.

In using the wall superheat and quality as the primary pair of independent variables, the concept of a boiling curve can be preserved and the definitions of "heat transfer surface" and "boiling curve" arise as they are used in this paper.

This selection of wall superheat and quality as the primary pair of independent variables also leads to what is believed to be a natural division of regions over which different correlations may be needed. In terms of quality, the subcooled, saturated, and superheated regimes can be defined. For wall superheat, different regimes of application are defined by the departure from nucleate boiling (DNB) and the minimum film boiling point (MFB). From this approach a "skeleton", upon which different correlations can be defined as to their regions of application, is obtained.

III. BLOWDOWN HEAT TRANSFER CORRELATION AND LOGIC

A "region of application" approach, shown in Figure 1, details the RELAP4/MOD6 blowdown heat transfer correlations and the regions in which they are applied.

Heat transfer correlations used for blowdown are complex due to their functional form and due to discontinuities that can be introduced by the switching logic. The discussion of this logic is presented in terms of the subcooled regime, saturated regime, and finally the superheated regime.

1. SUBCOOLED REGIME

The Dittus-Boelter[6] correlation evaluates heat transferred into the subcooled liquid under forced convection conditions. This flux is used until that determined from the modified Chen[7] correlation exceeds it, at which time a switch into the subcooled nucleate

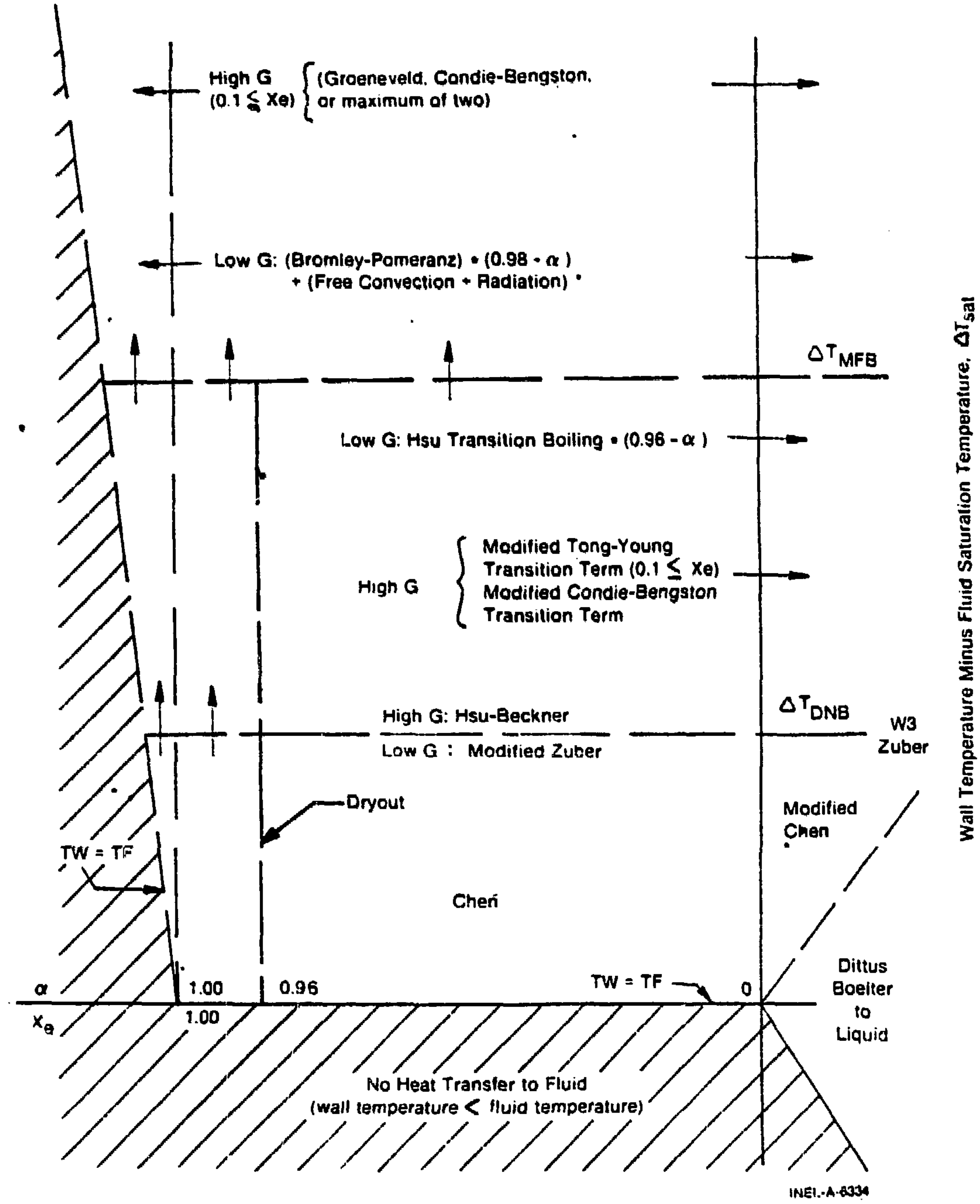

Fig. 1 RELAP4/MOD6 blowdown heat transfer correlations and regions of application.

boiling is assumed and the heat flux from the modified Chen is used. These two correlations represent the pre-DNB portion of the subcooled boiling region.

DNB for the subcooled high flow region, $G \geq 4.882\ (10^6)\ kg/(m^2 \cdot hr)$, is determined through the use of Tong's W-3 correlation[8]. DNB for the low flow,

$G \leqslant 9.764\,(10^5)$ kg/(m^2·hr), subcooled case used the Zuber[9] correlation. Zuber's subcooled correction is not used for low flow subcooled DNB because this correction is assumed to be seldom needed. For the transition window between these two flow limits, a linear interpolation of mass flux is used. A lower limit of the Zuber correlation is used if needed.

For the post-DNB portion of the subcooled regime, the same predryout correlations as will be discussed for the saturated region are used. Where correlations are a function of quality, a minimum value of 10% is used. This minimum was used since it is an approximate value of the lower limits of the data from which the correlations were developed.

The only known discontinuity in the subcooled region is a minor one in the *modified* Tong-Young transition boiling correlation[2] at DNB.

2. THE SATURATED REGIME

The Chen correlation[10] is used to represent the nucleate boiling phase of the saturated region. Four boundaries are shown which may be crossed in order to depart from this heat transfer regime. Quality may decrease until a subcooled nucleate boiling regime is reached ($X \leqslant 0$). Wall temperature may drop until reverse heat transfer is realized ($\Delta T_{sat} < 0$). Dryout will occur when the void fraction exceeds 0.96, and dispersed flow then results. A DNB may occur and a transition heat transfer regime will be reached.

For the high flow case, $G \geqslant 4.882\,(10^6)$ kg/(m^2·hr), q_{DNB} is defined by Hsu and Beckner's modified W-3 correlation[2]. For the low flow case, $G \leqslant 9.764\,(10^5)$ kg/(m^2·hr), Smith and Griffith's modified Zuber correlation[11] is used to define q_{DNB}. The same transition from high to low flow as used in the subcooled region is used for the saturated region except that the modified Zuber correlation provides the lower limit. The dryout criterion on void fraction of 0.96 is consistent with the Hsu-Beckner correlation. This criterion is then extended into the low flow regime for use in the modified Zuber correlation.

In the post-DNB region where dryout has not been reached, the heat flux is found from

$$q_{\substack{\text{total}\\\text{post-DNB}}} = q_{\substack{\text{transition}\\\text{boiling}}} + q_{\substack{\text{film}\\\text{boiling}}} .$$

For the high flow case, $G \geqslant 9.764\,(10^5)$ kg/(m^2·hr), transition boiling may be defined by either the modified Tong-Young[2] or the modified Condie-Bengston[2] correlations. For the low flow case, $G \leqslant 4.882\,(10^4)$ kg/(m^2·hr), a modified Hsu[2] transition boiling correlation with void fraction weighting to represent the amount of liquid surface area available is used.

For the film boiling high flow case, the heat flux may be determined one of three ways. Groeneveld's nonequilibrium film boiling correlation[12] may be used, Condie-Bengston's film boiling correlation[2] may be used, or the maximum of Groeneveld and Condie-Bengston may be used. However, the Condie-Bengston correlation generally will yield larger heat fluxes than the Groeneveld correlation such that the maximum of the two options is not advisable. For the low flow film boiling case, the Bromley-Pomeranz film boiling correlation[13] and the free convection plus radiation correlation[2] are used. Both are weighted using void fraction to represent the amount of vapor surface area available for heat transfer.

Once dryout occurs, the appropriate film boiling correlation alone is used. This change is used for both dryout from the nucleate boiling regime or dryout from the transition boiling regime.

As indicated earlier, an effort has been made to eliminate or identify the discontinuities which exist when changing from one correlation to another. At DNB, major modifications were made to the original transition correlations to ensure continuity across ΔT_{DNB}. For the modified Tong-Young correlation, a minor discontinuity with respect to ΔT_{DNB} still exists. For transition from the high to the low flow correlations, the discontinuity was eliminated by evaluating both the high and low flow correlations in the range $4.882\,(10^4)\ \mathrm{kg/(m^2 \cdot hr)} < G < 9.764\,(10^5)\ \mathrm{kg/(m^2 \cdot hr)}$ with the maximum heat flux used. This procedure was found to provide a continuous heat flux with respect to mass flux for the present set of correlations. At dryout, discontinuities still exist for both the pre-DNB and post-DNB transition regimes for both the high or low flow cases.

3. THE SUPERHEATED REGIME

The superheated regime is an extension of the dryout case for the saturated regime. Thus, the film boiling correlations are used. No known discontinuities exist for this regime.

IV. BLOWDOWN EXPERIMENTAL DATA COMPARISONS

Evaluation of the RELAP4/MOD6 blowdown heat transfer surface was made by several experimental data comparisons. Two of these comparisons have been chosen to demonstrate the predictive capability of this model and the hydraulic model. The two experimental data comparisons, EG&G Semiscale Experiment S-02-9[4,14] and ORNL THTF Test 105[5,15] are presented in this section with a discussion of the analysis and data.

1. EG&G SEMISCALE DATA COMPARISONS

The Semiscale Mod-1 experimental program is a part of the NRC investigation of the thermal and hydraulic phenomena accompanying a hypothetical loss-of-coolant accident (LOCA) in a nuclear reactor system. The Semiscale system consists of an upper and lower plenum, downcomer, core simulator containing 40 electrically heated rods, and intact and broken loops. The electrical heater rods are shorter (1.68 m) than those of a nuclear reactor. Semiscale Test S-02-9 was selected for predictive capability comparison to data; Test S-02-9 conditions were from full pressure (15.7 MPa) and power (1.44 MPa) with a peak density of 39.7 kW/m.

The RELAP4/MOD6 model for Semiscale Test S-02-9 used 47 fluid volumes to represent the experimental system. Two separate flow channels with five fluid volumes each were used to simulate the heated core. This arrangement was designed to represent the core region for Semiscale tests with radially peaked power profiles as well as for those tests with flat radial power profiles such as Test S-02-9. The heat slabs (20) in this region were nodalized axially to be consistent with the heater rod power steps.

Predicted and measured core inlet flows were compared and showed reasonable agreement. Predicted and measured heater rod temperatures are presented for two axial levels in Figure 2. Cladding temperature for the midcore (0.66 m) section was well predicted. The upper (1.32 m) region of the core shows an early CHF with a corresponding overprediction of measured temperature. This early CHF prediction at the top of the core has been observed in other Semiscale predictions and represents a limitation in the RELAP4/MOD6 calculation.

2. ORNL THTF DATA COMPARISONS

The THTF program is an experimental separate effects study of the thermal and hydraulic response of a simulated PWR core during blowdown being conducted by Oak Ridge National Laboratory. The system contains core simulator, upper and lower plenum and downcomer, pump, pressurizer, heat exchanger, and associated piping. The core region contains 49 electrically heated rods 3.66 m in length and 1.07 cm in diameter. The experiment selected was THTF Test 105 which simulated a large cold leg break in a PWR from full pressure and peak power density of 55.6 kW/m. Test conditions and facility descriptions are presented in the THTF test reports[5,16].

The RELAP4/MOD6 model has nine axial core volumes which represent one per heat rod power step. These models represent a core model which is driven by inlet and outlet boundary conditions calculated from a system model. The inlet and outlet flows for measured and calculated mass flow were compared and showed good agreement. Two axial levels were selected for cladding temperature comparisons and are presented in Figure 3. The lower portion (0.94 m) of the core was well predicted. The upper section (3.18 m) of the THTF core was not predicted well by RELAP4/MOD6 because of a predicted CHF

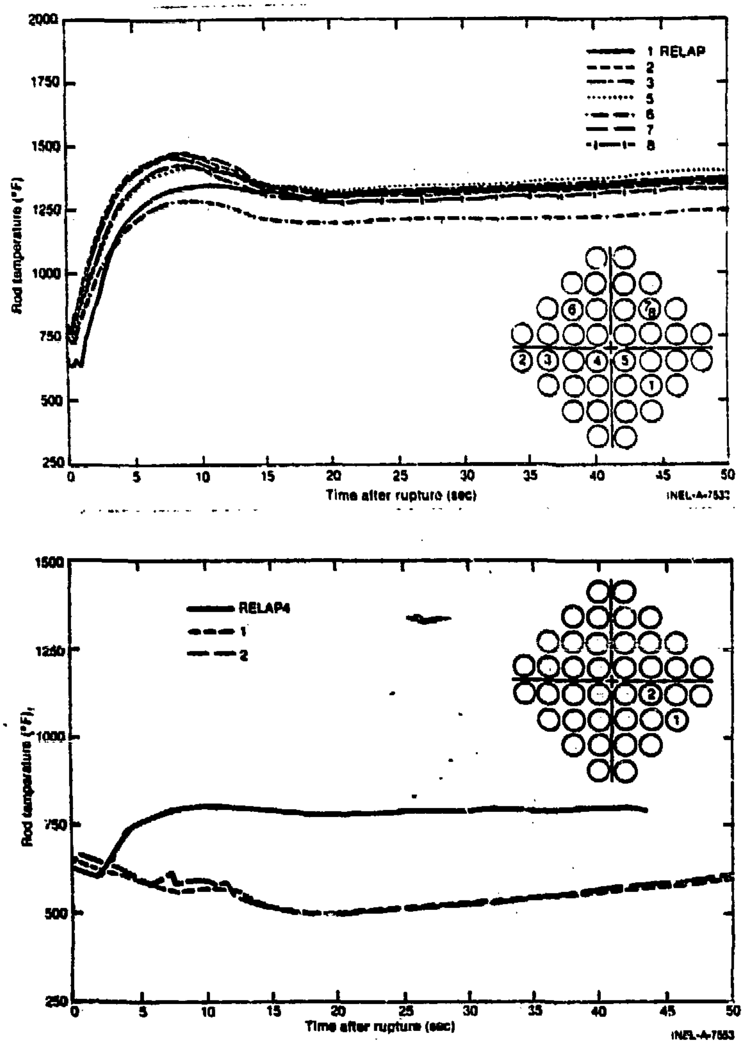

Fig. 2 Predicted and measured heater rod temperatures for Semiscale Test S-02-9.

which did not occur in the data. This predicted CHF where the experimental temperatures do not indicate a CHF was observed in other THTF test comparisons and the preceding Semiscale results and represents a limitation in the RELAP4/MOD6 calculation.

V. CONCLUSIONS

The RELAP4/MOD6 blowdown heat transfer correlations and logic have been presented along with the CHF correlations. Two experiments, Semiscale S-02-9 and THTF 105 data comparisons were presented using the blowdown heat transfer surface. In both cases, the core flow was reasonably predicted and temperature results for the lower and mid-core regions were well predicted. The predictions for the upper core regions in both

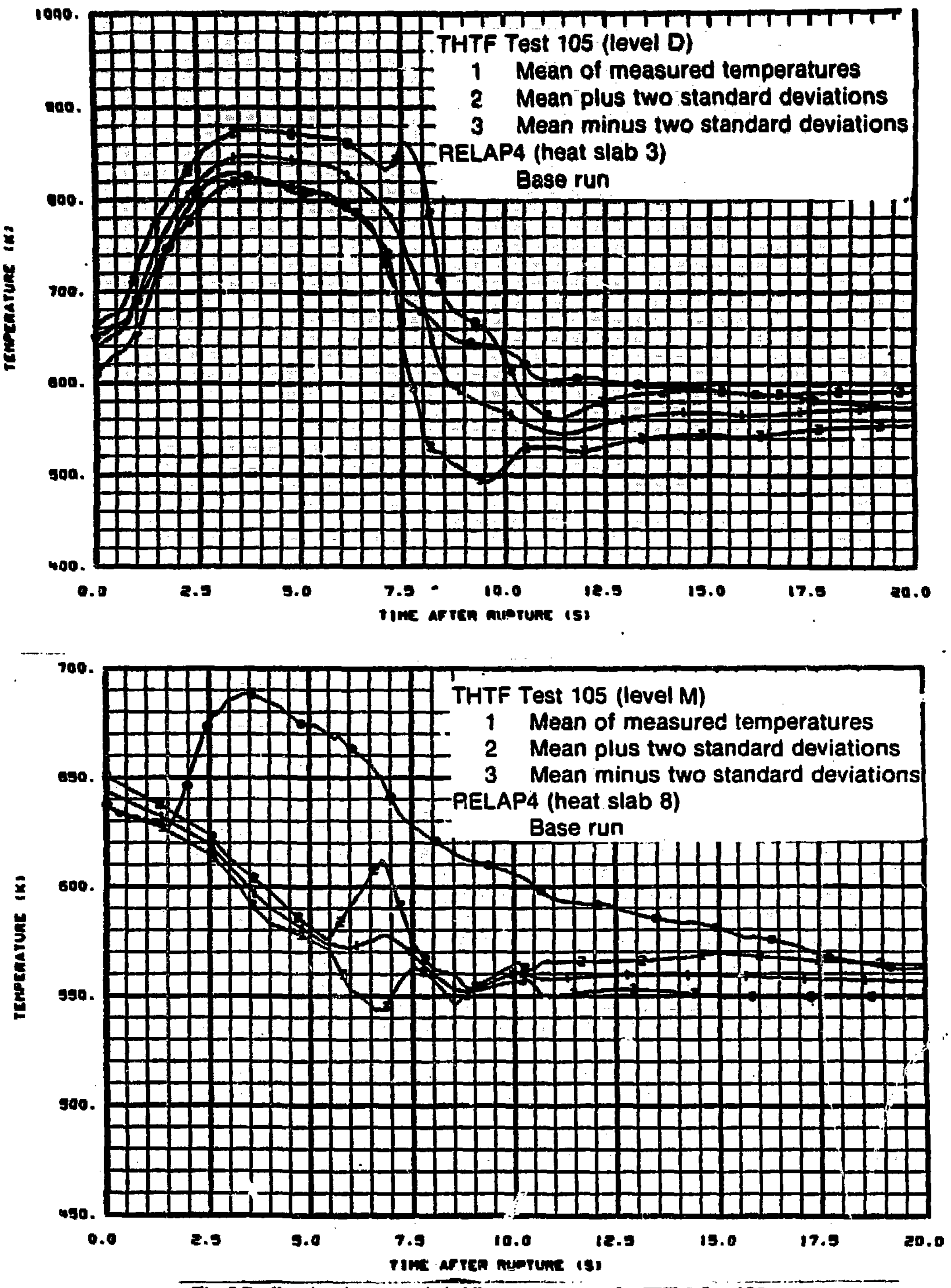

Fig. 3 Predicted and measured cladding temperatures for THTF Test 105.

experiments showed an early CHF which was not confirmed by measured temperatures. This showed a limitation in the RELAP4/MOD6 prediction of the upper region of the core. This early CHF prediction does not appear to be height dependent since Semiscale represents a short (1.67 m) core while THTF represents a full length (3.65 m) core. It is not currently possible to determine whether this limitation arises within the hydraulic prediction, the CHF calculation, or a combination of the two.

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