RECENT IMPROVEMENTS TO STEADY-STATE THERMAL-HYDRAULIC ANALYSIS OF RESEARCH REACTORS AT ANL

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ABSTRACT

Recent reactor conversion studies in the RERTR Program have required expansion or revision of modeling capabilities for steady state thermal-hydraulic analysis. For example, some reactors operate in laminar flow, necessitating new correlations for Nusselt number and for friction loss. Others have single-sided heating of edge channels. And some have geometrical details that require new modeling approaches to either simulate or validate. Computational fluid dynamics was compared with the 2-dimensional approximation to heat flow used by the PLTEMP/ANL V3.0 code. A very systematic approach to hot channel factors is implemented. A closed-form solution is now used in flat-plate geometry to improve both speed and accuracy of the solution. Direct heating to clad and coolant is now included. The Groenveld table lookup method is now available for determination of CHF. Flow excursion prediction is updated. All of these improvements have been incorporated in the PLTEMP/ANL V3.0 code.

1. Introduction

In the past, steady-state thermal-hydraulic analysis of research reactors within the RERTR Project was directed at reactors operating in turbulent flow. Recent conversion studies have required extending the flow regime to laminar, including the transition between laminar and turbulent. The details of fuel assembly design are quite varied, requiring more flexibility in modeling than was available. New approaches to CHF and flow instability are available. In addition, validation is increasingly important. This work covers updates to modeling methods, to hot channel factors, to correlations, and to validation.

2. New Approach to CHF and DNBR Prediction

As part of the process of updating and improving PLTEMP [1], selected correlations and logical methodology used by the RELAP5/3D (ATHENA) code have been incorporated. The RELAP5/3D code uses the CHF lookup table method [2]. A more recent version of the lookup table is available, and was recently added to PLTEMP. [3].

For the University of Florida Training Reactor conversion project, it was necessary to provide new capabilities to PLTEMP that enabled modeling friction factors and heat transfer correlations for laminar flow. Critical Heat Flux table lookup from Groeneveld

(as used by RELAP5/3D) is now available as a more accurate method from which to obtain the Departure from Nucleate Boiling Ratio, DNBR. Correction factors can be applied to the base CHF table to account for changes in hydraulic diameter:

$$K_1=(0.008/D_h(m))^{0.33}$$

Other effects such as from the use of bundles (K_2), grids (K_3), heated length variation (K_4), axial flux distribution factor (K_5), radial or circumferential flux distribution factor (K_6), flow-orientation factor (K_7), and vertical low-flow factor (K_8), have been developed by Groeneveld and others for use with the CHF tables. Only K_1 is accounted for in our present version 3.0 of PLTEMP. The lookup tables are appropriate for pressures ranging from 0.100 MPa to 20 MPa, mass fluxes from 0 to 8000 kg/m^2/s, and quality from -0.5 to 1.0. Because PLTEMP is only valid for 1-phase flow, it is used for quality from -0.5 to 0.0. The tables are appropriate for upflow and downflow. End-point values for mass flux and quality are used rather than permitting extrapolation. Linear interpolation in pressure is used to create a temporary CHF lookup table appropriate to the pressure of the problem, prior to a full solution in PLTEMP. Two-dimensional interpolation within (flux, quality) points is used to yield a CHF. The table accuracy is quoted as: 87% of data is within ± 10%; and the rms error is 7.82 %.

3. Changes For Laminar Flow

One-sided heat transfer can be modeled for first and last coolant channels in a fuel assembly (this is important for laminar flow only, as in the Florida Training Reactor):

$$Nu=4.86.$$

The laminar flow heat transfer coefficient is computed and compared with the turbulent flow value. The larger heat transfer coefficient is then used. The ORNL laminar forced convection correlation is:

$$Nu=7.63.$$

Channel friction factors can now be computed for laminar flow, and for the transition between laminar and turbulent flow. The laminar friction factor in a narrow rectangular channel is calculated from:

$$f=96/Re, \text{ for } 0 < Re < 2200$$

Corrections for a non-circular flow channel or for a thick annulus are available theoretically but are not yet implemented. In the transition region between laminar and turbulent flows, the friction factor is computed by reciprocal interpolation as

$$F_{l,t} =(3.75-8250/Re)(f_{t,3000}-f_{l,2200}) + f_{l,2200} \qquad 2200<Re<3000$$

where $f_{l,2200}$ is the laminar factor at a Reynolds number of 2200, $f_{t,3000}$ is the turbulent friction factor at a Reynolds number of 3000. The turbulent friction factor $f_{t,3000}$ is found recursively from the Fanning friction factor equation.

4. Flow Instability Prediction

Prediction of the onset of flow instability is revisited in a companion paper [4]. PLTEMP includes two correlations for predicting the onset of excursive-flow instability that are based on the work of Whittle and Forgan [5]. PLTEMP edits "MINIMUM FLOW INSTABILITY POWER RATIO," FIR. It is based on Whittle and Forgan's

$$R = \frac{1}{1 + \eta\, D_H / L_H}$$

D_H is the heated diameter of the channel and L_H is the heated length. The flow instability factor supplied to PLTEMP is η. This is based upon a statistical evaluation of the rectangular channel data of Whittle and Forgan, that determined the 95% single-sided limiting probability P(X<0.95). From the Student "t" distribution, using a=-∞, b=1.666, yields P(η<31.09)=0.95. This yields a 95% confidence interval that 95% of the *rectangular channel* data measured by future measurements will not exceed 31.09. **It is recommended that the limiting value for η be 32.5, consistent with the recommendation in [6].**

The ORNL Advanced Neutron Source Reactor design team proposed the following correlation, which is a modification of the Saha-Zuber correlation:

$St = q''/(G\, C_p\, \Delta T_{sub}) = 0.0065$ Pe>70,000, Saha-Zuber

$St = q''/(G\, C_p\, \Delta T_{sub}) = 0.0065\, \eta_{sub}$ Pe>70,000, ORNL ANSR

Where $\eta_{sub} = 0.55 + 11.21/\Delta T_{sub}$ is the proposed subcooling correction factor. The Stanton number, St, is much better fitted at low exit subcooling (i.e. less than 20 C) by the ORNL ANSR modification. This new correlation was added to the edits from PLTEMP 3.0 as a Flow Excursion Ratio, FER. It is the minimum ratio of predicted excursion heat flux to actual heat flux, at all axial nodes and all heated surfaces.

PLTEMP also edits the local value at every heated surface node midpoint for $\eta' = V\Delta T_{sub0}/q$, units of K cm^3/J when velocity V is cm/s, temperature difference in K, and q is W/cm^2, and $\Delta T_{sub0} = T_{sat} - T_b$. This is similar to the Whittle and Forgan FIR, but applied locally to account for axial power shape variation.

5. Hot Channel Factor Usage

Methods for determining hot channel factors for research reactors are documented in [7, 8, 9]. This treatment uses the following six hot channel factors.

Global (reactor system-wide) factors:

F_{power} = A factor to account for uncertainty in total reactor power measurement.
F_{flow} = A factor to account for uncertainty in total reactor flow measurement.
F_h = A factor to account for uncertainty in heat transfer coefficient.

Local (random hot spot) factors:
F_{bulk} = A factor for local bulk coolant temperature rise
F_{film} = A factor for local temperature rise across the coolant film
F_{flux} = A factor for local heat flux from cladding surface

The usage of hot channel factor F_h is changed; it is now applied globally rather than locally.

6. Changes to Solution Technique

The previous version of PLTEMP (V2.14) used a multidimensional search process to locate the point within each fuel plate or tube at which the peak fuel temperature occurred. This process has worked well, but takes appreciable time when the problem contains multiple fuel assemblies, many plates, and many axial nodes. We have found that there are reactor situations where there will not be a temperature peak other than at one edge of a fuel plate, when there is massive cooling on one side of a plate. In that event, the search process has failed. In order to overcome that failure, a closed-form solution has been made an option. The closed-form solution also makes possible allocating a fraction of fission heat directly into clad or into coolant, thereby simulating gamma transport and absorption. Furthermore, the closed-form solution accounts for the dependence of coolant enthalpy on pressure. This enthalpy dependence on pressure becomes important for fuel assemblies in a high-powered research reactor operating at high coolant mass flow rates, where the pressure difference from channel inlet to outlet may exceed a few bars.

A typical Safety Analysis Report requires generating a Power vs. Flow map of the operating region. One needs to know the pressure drop that yields a prescribed mass flow rate. One also needs to know the power required to obtain a prescribed limiting ONB Ratio. A two-level search is now automated to obtain these key results.

7. Natural Convection Flow Solution

Natural convection modeling of friction factors and heat transfer correlations as used in NATCON [7] have been added to PLTEMP, and will be made operational in FY07. NATCON uses forced-flow laminar correlations. THE NATCON code is also available in a version for fuel pins that is useful for analysis of MNSR's and TRIGA's. It has recently been updated to span a wider range in pitch-to-diameter ratio, and to use hot channel factors consistent with the latest implementation in PLTEMP/ANL V3.1.

8. Validation: The effect of 2D vs. 3D Modeling

Detailed MCNP calculations for the University of Florida UFTR showed that individual fuel plates had a peak/average power ratio of up to 1.31 across the width of the plate, as shown in Fig. 1. The PLTEMP code accounts for axial power density variation, and models each plate uniquely. But it does not model power density variations in this third direction, across the width. What impact does this have on predicted reactor safety margins? To answer that question, two test problems were posed for a single plate with a typical axially peaked power profile, which could be solved by either PLTEMP or by a

3D CFD technique. As in any plate-type reactor fuel, the fuel meat does not occupy all of the width of the plate: the edges act as fins, spreading heat laterally. Also, in fuel assemblies consisting of a series of plates, there is *lateral heat conduction through fuel plates* that tend to mitigate peak clad and coolant temperatures. The PLTEMP code captures the lateral heat conduction directly in its solution, and captures the fin effect indirectly by accounting for the heated area, heated perimeter, wetted area, and wetted perimeter.

Figure 2 illustrates how the clad surface temperature varies across the face of a single fuel plate, when computed in full 3D geometry by a CFD method [10]. One can see that the temperature variation across the width is greatly reduced, in particular, at the upper (hottest) end. This is the key location because of its impact on the Onset to Nucleate Boiling ratio, which is a design limiting parameter. For this reactor, the peak ONB occurs very near the upper end of the fuel plate meat.

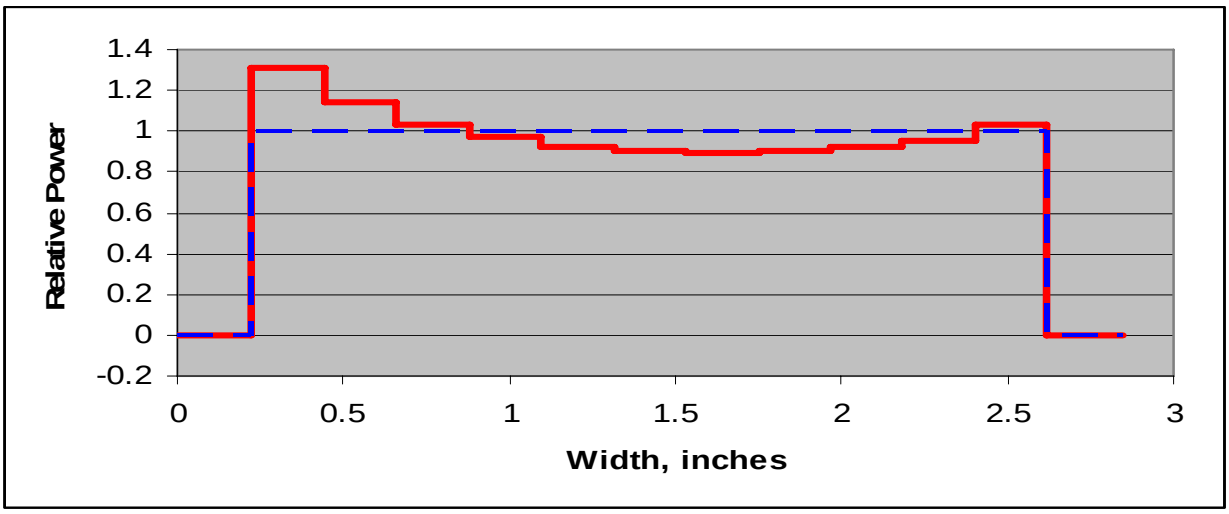

Fig. 1 Transverse Power in a Single UFTR Fuel Plate

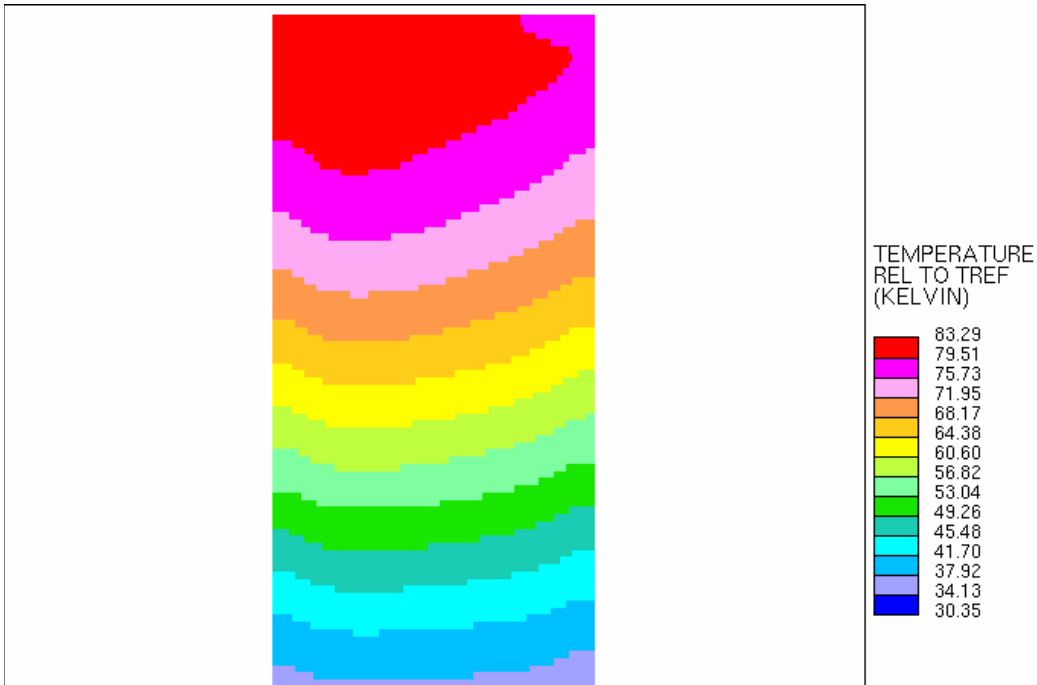

Fig. 2 Clad Temperature Distribution in a UFTR Fuel Plate: CFD Solution

There was remarkably little difference between the 3D CFD solution and the PLTEMP solution in 2D: only an 0.6 C difference in peak clad temperature for a realistic case with the full 2D power density profile, and 1.9 C difference when the power density profile was simplified to 1D (no variation across the width). In each case, the PLTEMP solution was conservative, indicating that its predictions could be used without modification. We caution that this conclusion only applies to the UFTR, which has laminar flow, a very low heat flux, and limiting conditions at the top of the fuel meat. We expect to perform similar comparisons for other reactor conversion projects in future in order to quantify the importance of this 3D effect for each reactor.

9. Conclusions

Continuous improvement in modeling methods and techniques follows from the needs of the licensing process for conversion of research reactors. Steady-state methods as implemented in PLTEMP/ANL V3.1 have been (or are being) successfully applied to a variety of recent reactor conversion studies (UFTR (Florida), RPI (Portugal), VR-1 (Prague), MIT (Massachusetts)). More advanced methods such as CFD have been helpful to confirm the importance (or lack thereof) of modeling details that are beyond the spatial heat transfer capabilities of PLTEMP/ANL V3.1.

10. Nomenclature

C_p	specific heat, J/kg-K
D_H	heated equivalent diameter, m
G	mass flow rate, kg/m^2-s
L_H	heated length, m
Nu	Nusselt Number
Pe	Peclet Number
Re	Reynolds Number
V	velocity, cm/s
f	friction factor
q''	heat flux
η	Flow instability parameter, dimensionless
η'	$V\Delta T_{sub0}/q$; a local flow instability parameter (units of K-cm^3/J)

ΔT_{sub} Subcooling, T_{sat}-$T_{b;}$ T_{sat} is the saturation temperature and T_b is the bulk temperature
ΔT_{sub0} Subcooling, $T_{sat\ exit}$-$T_{out;}$ T_{out} is the bulk fluid exit temperature

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