An Update To The Multitasking Thermalhydraulics Evaluation Package

Y. Guo, L.K.H. Leung, and A. Vasic
Chalk River Laboratories, Atomic Energy of Canada Limited
Chalk River, ON, K0J 1J0

Abstract

An update of the multitasking Thermalhydraulics Evaluation Package (TEP) was implemented to improve the prediction accuracy of critical heat flux (CHF) and post-dryout (PDO) heat transfer for 37-element fuel bundles. The improvement of prediction accuracy was achieved using the latest correlations for CHF and PDO heat transfer derived from full-scale bundle tests. The predictions of TEP were assessed against experimental data and good agreement has been observed. In addition to the improvement, the prediction capability of the package has been expanded to capture the effect of radial power profile on CHF for 37-element bundles. A correlation for the radial power profile effect on CHF has been implemented. It accounts for the deviation in CHF between the bundle of radial power profile of interest and the equivalent bundle of the natural uranium profile.

1. Introduction

Accurate predictions of heat-transfer rate and pressure loss are essential in thermalhydraulic analysis of flow-boiling systems such as boilers, heat exchangers, steam generators, reactor fuel channels, etc. A variety of heat-transfer and fluid-flow correlations have been recommended in the literature. The choice of a correlation for a particular application depends on the heat-transfer mode and flow regime, as well as geometry, orientation of the surface, direction of the flow-velocity vector, and local phase distribution. Most correlations require numerous fluid properties and may need iterations to evaluate parameters of interest.

A software program, the Thermalhydraulics Evaluation Package (TEP), has been introduced to facilitate the thermalhydraulic analysis of flow-boiling systems. This evaluation package was originally developed 20 years ago to simplify the evaluation procedure. The core of TEP is a package for thermalhydraulics and fluid-properties predictions written in FORTRAN. It can be easily implemented into existing computer codes as a library for the evaluation of thermalhydraulics parameters.

As a powerful multitasking software package for evaluation of thermalhydraulics parameters in tubes and bundles in horizontal and vertical orientations, TEP is an ideal tool for simple desktop calculations in the design of two-phase flow systems with or without boiling. It is also an excellent tool for sensitivity analysis of minor variations in design conditions on thermalhydraulic parameters. For example, the impact of geometry tolerances and flow-condition fluctuations on heat transfer or pressure drop can easily be examined with TEP by modifying the input parameters and conditions. In addition, TEP has the capability of evaluating the pressure and temperature distributions in channels with non-uniform axial heat fluxes. This allows the use of TEP to assess the thermalhydraulic performance in boiling systems (such as a reactor fuel channel) for given inlet-flow conditions.

The previous version of TEP (TEP V3.0) was completed in 1998 [1]. It implemented various prediction methods for critical heat flux (CHF), post-dryout (PDO) heat transfer, and pressure drop derived prior to 1998. Since then, some prediction methods, particularly those for CANDU®[1] type bundle geometries, have been updated. Furthermore, additional correlations were derived for other applications (e.g., taking into account radial power profiles other than that of natural uranium fuel in CANDU-type bundles). TEP has been updated to implement the improved prediction methods and recently derived new correlations. The new version (β-release, 2006) is referred as TEP V3.3, which has enhanced features and expanded capabilities. The objective of this paper is to present this new TEP version and the assessment result against full-scale bundle data.

2. Main Features of TEP

TEP has four main features: specific thermalhydraulics-parameter evaluation, local heat-transfer evaluation, system flow and heat-transfer evaluation, and fluid-properties evaluation.

The first feature is used to evaluate a user-specified thermalhydraulics parameter based on user-input flow conditions. It is introduced primarily for sensitivity analyses by applying the prediction methods within and beyond the applicable range and transition points. This feature includes all heat-transfer modes (i.e., single-phase heat transfer, nucleate boiling, transition boiling, film boiling), the transition points between various heat-transfer modes (i.e., CHF, Minimum Film Boiling (MFB) temperature), frictional pressure drop, void fraction, and flow regime.

The second feature evaluates local heat-transfer rates and surface-temperature values at user-input local-flow conditions. The program identifies heat transfer regimes based on the pre-defined heat-transfer logic. The procedure for determining the heat-transfer mode is different for a heat-flux controlled system than for a wall-temperature controlled system. Depending on the user input (i.e., known heat flux or known wall temperature), the program chooses an appropriate procedure automatically.

The third feature evaluates distributions of thermalhydraulics parameters (such as pressure, surface temperature, thermodynamic quality, etc.) along a channel based on the user-specified inlet-flow conditions. The system heat-transfer calculation begins with a nodalization process to divide the overall channel into nodes axially. At each node, the local pressure is calculated by subtracting the pressure drops caused by friction, acceleration, gravitation (for vertical channels only), and fuel element appendages from the upstream pressure. The thermodynamic quality is calculated with a heat balance assuming thermal equilibrium between the liquid and vapour phases. Based on the local flow parameters, the local heat-transfer mode is determined with the heat-transfer logic for a heat-flux-controlled system. The corresponding heat-transfer rate and wall temperature are then calculated with the prediction method for the heat-transfer mode. These procedures are repeated for all nodes until the end of the heated section is reached.

[1] CANDU - CANada Deuterium Uranium (a registered trademark of AECL).

The last feature evaluates the fluid properties based on the user input of pressure and temperature (or enthalpy). This feature provides all properties that are needed in thermalhydraulic calculations.

3. Update to TEP V3.0

TEP V3.3 is an update of its previous version (TEP V3.0), and retains all features from TEP V3.0 [1]. The update reflects the up-to-date development and improvement in prediction methods of thermalhydraulics parameters to improve the capability and application of the program. It focuses on the prediction methods of CHF and PDO for circular-array (37-element) bundle geometry. Existing calculation procedures in TEP V3.0 for tubes and square-array bundles remain unchanged in TEP V3.3.

The following improvements have been made in TEP V3.3:

- The updated CHF look-up table was implemented to improve the prediction accuracy for 37-element bundles with NU fuel in an uncrept channel.
- A prediction method for the effect of radial power profile on CHF was implemented to facilitate analyses of circular-array bundles with fuels other than natural uranium (NU).
- A prediction method for the effect of pressure-tube creep on CHF was implemented to extend the TEP application to aged CANDU channels.
- A correction factor accounting for geometry effect on CHF was implemented to extend the TEP application to fuel bundle configurations other than that of the current 37-element bundle.
- An interpolation correlation for developing film boiling heat transfer was implemented to predict the film-boiling heat transfer coefficient in the transition region.
- An additional formulation (HLWP-01) for evaluating light- and heavy-water properties, with pressure and enthalpy as input parameters, was added as a new option.

Input parameters required for TEP V3.3 are the same as those for TEP V3.0. The only exception is the parameter of radial heat flux distribution (RFD) for circular-array bundles. TEP V3.0 has a built-in (fixed) RFD corresponding to the NU fuel. TEP V3.3 allows the user to specify different RFDs.

<u>CHF look-up table for 37-element bundles with NU fuel in an uncrept channel</u>

The 1997 version of the look-up table for CHF in horizontal 37-element bundles [2] is used in TEP V3.0. This table was derived based on the tube CHF table and updated with experimental data obtained with a full-scale 37-element bundle string inside the uncrept channel at the Stern Laboratories and NRU U-1 CHF test facility. Since then, more CHF data have become available with a full-scale 37-element bundle string in uncrept and crept channels. The CHF look-up table was subsequently updated with those newly obtained CHF data (the CHF data obtained in crept channels was converted to that in the uncrept channel using a correlation factor, as presented below), resulting in a significant improvement in predicting CHF for CANDU 37-element fuel bundles. The updated CHF look-up table, referred hereafter as the 2001 bundle CHF table, also extended the table application to crept channel conditions, and covered a wider parametric range.

The 2001 bundle CHF table has the structure and application method identical to those of the 1997 version. The 2001 bundle CHF look-up table replaced the 1997 version in TEP V3.3.

Correction factor for RFD effect on CHF

The CHF look-up table was developed for a direct application to the 37-element bundles with an NU fuel RFD. A correction factor for RFD effect on CHF has been developed to expand the CHF look-up table application to bundles having RFDs other than that of NU fuel. Yin et al. [3] recommended a correction factor for the 37-element bundle application. The correction factor is defined as:

$$K_{rfd} = \frac{CHF\ for\ Flux\ Shape\ of\ Interest}{CHF\ for\ Flux\ Shape\ of\ NU\ Fuel} \tag{1}$$

Based on the experiment data obtained with 37-element bundles having various RFDs, Yin et al. derived a correlation for the correction factor, expressed as:

$$K_{rfd} = a_1 - a_2(Z-1) \tag{2}$$

where a_1 and a_2 are constants determined experimentally, Z is the bundle-imbalance factor between the RFD of interest and the optimum RFD[2]:

$$Z = \max[R'_i] \qquad i = Ring\ 1,2,3,4 \tag{3}$$

with

$$R'_i = R_i / R_{i,o} \tag{4}$$

where R_i and $R_{i,o}$ are the local to bundle-average heat-flux ratings of Ring i for the RFD of interest and the optimum RFD, respectively. Equation (2) was empirically derived, based on the tested RFDs in 37-element bundles, and hence has limited applications.

The RFD correction factor can also be expressed with respect to the optimum RFD rather than the one of the NU fuel [3]. It is defined as:

$$K_{rfdo} = \frac{CHF\ for\ Flux\ Shape\ of\ Interest}{CHF\ for\ Optimum\ Flux\ Shape} \tag{5}$$

Combining Equations (1) and (5) one obtains:

$$\begin{aligned} K_{rfd} &= \frac{CHF\ for\ Flux\ Shape\ of\ Interest}{CHF\ for\ Flux\ Shape\ of\ NU\ Fuel} \\ &= \frac{CHF\ for\ Flux\ Shape\ of\ Interest / CHF\ for\ Optimum\ Flux\ Shape}{CHF\ for\ Flux\ Shape\ of\ NU\ Fuel / CHF\ for\ Optimum\ Flux\ Shape} \\ &= \frac{K_{rfdo}}{K_{rfdo}(NU)} \end{aligned} \tag{6}$$

[2] The optimum RFD is the RFD where initial dryout occurs simultaneously at every ring of the bundle, and is corresponds to the maximum attainable dryout power.

where

$$K_{rfdo}(NU) = \frac{CHF\ \ for\ Flux\ Shape\ of\ \ NU\ \ Fuel}{CHF\ \ for\ Optimum\ Flux\ Shape} = \frac{1}{K_{rfd}(Optimum)} \tag{7}$$

From Equation (2), K_{rfd}(Optimum) = 1.28 for the 37-element bundles. Therefore, CHF for optimum flux shape can be calculated by

$$CHF\ \ for\ Optimum\ Flux\ Shape = CHF\ \ for\ Flux\ Shape\ of\ \ NU\ \ Fuel \times K_{rfd}(Optimum) = 1.28 \times CHF(Look - Up\ Table) \tag{8}$$

Yin et al. [3] examined the relation between Z and R_{rfdo} using 37-element and 43-element bundle data, and found a simple linear function:

$$K_{rfdo} = 2 - Z \tag{9}$$

This function is applicable to both 37-element and 43-element bundles, and hence is considered to be more generic than Equation (2). Bundle CHFs of a given RFD can then be evaluated with Equations (5), (8) and (9). However, it is less accurate then the method of Equations (1) and (2) for the current 37-element bundles. Both these methods were implemented in TEP V3.3 to account for the RFD effect on CHF in the current 37-element bundles and other circular-array bundles, respectively, with an automatic selection of the prediction method based on the given fuel bundle geometry.

Correction factor for creep effect on CHF

The correction factor for creep effect on CHF is defined as

$$K_{creep} = \frac{CHF_{crept}}{CHF_{uncrept}} \tag{10}$$

where CHF_{crept} and $CHF_{uncrept}$ are the CHF values for a crept and an uncrept channel, respectively, at given thermalhydraulic conditions. $CHF_{uncrept}$ can be calculated using the 2001 CHF look-up table. By applying Equation (10), one can extend the application of the 2001 CHF look-up table to crept channel conditions.

Based on experiment data obtained with 37-element bundles in crept and uncrept channels, Leung derived a correction factor of K_{crept} to account for the effect of creep on CHF. His correlation is expressed in the form of

$$K_{creep} = exp\left(-b\left(1 - \frac{(1-\varepsilon)}{(1-\varepsilon_{uncrept})}\right)\right) \tag{11}$$

where b is a constant determined empirically, and ε is the bundle eccentricity, representing the relative distance of the centres between the bundle and the flow tube. ε is defined as

$$\varepsilon = \frac{D_{P/T} - D_{bundle}}{D_{P/T} - D_{inner}} \tag{12}$$

where $D_{P/T}$ is the diameter of the pressure tube in metres for a bundle at the location of interest. The pressure-tube diameter varies with axial locations along the crept channel.

The equivalent inner-tube (virtual) diameter of an annulus, D_{inner}, represents the weighted-average distance of elements from the centre of the bundle. It is expressed as

$$D_{inner} = \begin{cases} \dfrac{\sum_{i=1}^{N_r} n_i d_i^2 D_{r,i}}{\sum_{i=1}^{N_r} n_i d_i^2} & if \ n_1 > 1 \\ d_1 + \dfrac{\sum_{i=2}^{N_r} n_i d_i^2 D_{r,i}}{\sum_{i=2}^{N_r} n_i d_i^2} & if \ n_1 = 1 \end{cases} \tag{13}$$

In Equation (13), n_i and d_i are, respectively, the number and diameter (in metres) of elements in Ring i (with 1 being the centre ring (rod) and counting outwards), $D_{r,i}$ is the pitch-circle diameter in metres of Ring i, N_r is the number of ring (e.g., N_r=4 for the current 37-element bundle), and d_1 is the centre-element diameter in metres. The overall bundle diameter, D_{bundle}, in Equation (12) is calculated using

$$D_{bundle} = D_{r,N_r} + d_{N_r} + 2t_{bp} \tag{14}$$

where $D_{r,Nr}$, d_{Nr} and t_{bp} are the outer-ring pitch-circle diameter in metres, the outer-ring element diameter in metres, and bearing-pad height (i.e., the gap between the outer-ring element and pressure tube) in metres, respectively. The bundle eccentricity for the uncrept channel, $\varepsilon_{uncrept}$, corresponds to the reference pressure tube.

<u>Correction factor for bundle geometry effect on CHF</u>

The bundle CHF look-up table was derived for the current 37-element bundle. It can be extended to other circular bundle geometries with the following modification factor:

$$\frac{CHF}{CHF_{ref}} = \left(\frac{D_{bundle} - D_{inner}}{D_{bundle,ref} - D_{inner,ref}} \right)^n \tag{15}$$

where CHF is the critical heat flux for the bundle of interest, CHF_{ref} is the critical heat flux for a 37-element bundle (nominal geometry), and $D_{bundle,ref}$ and $D_{inner,ref}$ are the nominal bundle diameter in metres and the equivalent inner-tube diameter of a 37-element bundle with nominal geometry in metres, respectively. The exponent, n, which is only fluid dependent, is defined as

$$n = -0.5\left(1 - \exp\left(-0.35\left(\log\left(\rho_f / \rho_g\right)\right)^5\right)\right) \tag{16}$$

Interpolating correction for developing film boiling heat transfer

In TEP V3.0, two correlations are used to evaluate the film-boiling heat transfer rate for two flow regimes – the Groeneveld-Delorme correlation is used for the liquid-deficient regime and the Berenson correlation is used for the inverted annular flow regime. The maximum calculated heat-transfer coefficient is selected for predicting the film-boiling heat flux or wall temperature. This prediction method is based on an assumption that the liquid and vapour phases have become fully developed, hence the method tends to under-predict the film-boiling heat-transfer coefficient at near-CHF locations where both phases are still developing and heat transfer is enhanced. Rudzinski and Leung proposed a correlation to account for the heat transfer enhancement in predicting the minimum film-boiling heat transfer coefficient in 37-element bundles. This correlation is expressed as

$$K_{developing} = \frac{h_{min-film} - h_{fd}}{h_{nb} - h_{fd}} = c_1 \left(\frac{\rho_f}{\rho_g} \right)^{c_2} exp\left(-c_3 \left(\frac{\rho_f}{\rho_g} \right)^{c_4} (OHFR - 1)^{c_5} \right) \qquad (17)$$

for a given over-heat-flux ratio, OHFR.

In Equations (17), $h_{min-film}$ is the heat transfer coefficient of interest, h_{fd} is the fully-developed film-boiling heat transfer coefficient calculated with the same method as that in TEP V3.0 based on local flow conditions, h_{nb} is the nucleate boiling heat transfer coefficient evaluated with the Chen correlation based on local flow conditions, and ρ_f and ρ_g are saturated liquid and vapour densities, respectively. c_1 to c_5 are the constants determined using experimental data.

OHFR is defined as the ratio of local heat flux and predicted CHF at the point of interest.

HLWP formulation for evaluating light- and heavy-water properties

Liner and Hanna compiled a set of formulations for the Heavy and Light Water Properties (HLWP) package and developed corresponding FORTRAN subroutines for use in the CATHENA code [4]. The same subroutines are also used in the Advanced Solution of Subchannel Equations in Reactor Thermalhydraulics computer code (ASSERT). In these formulations, properties are calculated based on pressure and enthalpy. The HLWP properties formulations have been implemented as a new option in TEP V3.3 to predict light and heavy water properties based on given pressure and enthalpy.

4. Program Test, Verification, and Validation

A thorough process of program testing, verification, and validation was completed for TEP V3.0 and early versions of TEP. For the update of TEP V3.3, testing, verification and validation were performed during the coding process and after completion.

Testing of TEP V3.3 included both the unit testing of new and modified subroutines plus the integrated testing of the overall operation of TEP. The unit testing was performed by code developers during the coding stage, whereas the integrated testing focused on those stages that interact with users, for example user input.

Verification was applied to both the new and modified subroutines, as well as to the displayed screens in TEP V3.3. It focused mainly on the output information and the calculated results of TEP V3.3. A cross comparison of the TEP program calculation results with those obtained using alternative calculation methods was conducted to ensure each correlation had been implemented properly.

A validation process was performed by comparing the TEP predictions with experimental PDO heat transfer measurements of 37-element bundles. Figure 1 presents an example of the validation results, which compared the TEP prediction results from the system heat transfer calculation with a set of measurements of wall temperatures. The temperature variations were caused by bundle appendages. Correct parametric trends of temperatures have been captured by TEP V3.3. Given the complexity of the bundle configuration, thus the difficulty of the prediction, the measured temperatures were predicted with good accuracies.

5. Conclusion

TEP is a powerful tool for simple desktop calculations in the design of two-phase flow systems with or without boiling. It is also a useful tool for sensitivity analysis of minor variations in design conditions on thermalhydraulics parameters. It has the capability of evaluating pressure and temperature distributions of bundles having uniform and non-uniform power profiles in uncrept and crept channels, and can be applied in assessing the performance of two-phase systems for given inlet-flow conditions.

TEP has been updated to implement improved prediction methods and the new correlations derived since 1999. The update focused on the prediction methods of CHF and PDO for circular-array (37-element) bundle geometry. A new version of TEP (V3.3) has been released for use. The new version has extended features and provides improved prediction accuracies over the previous versions.

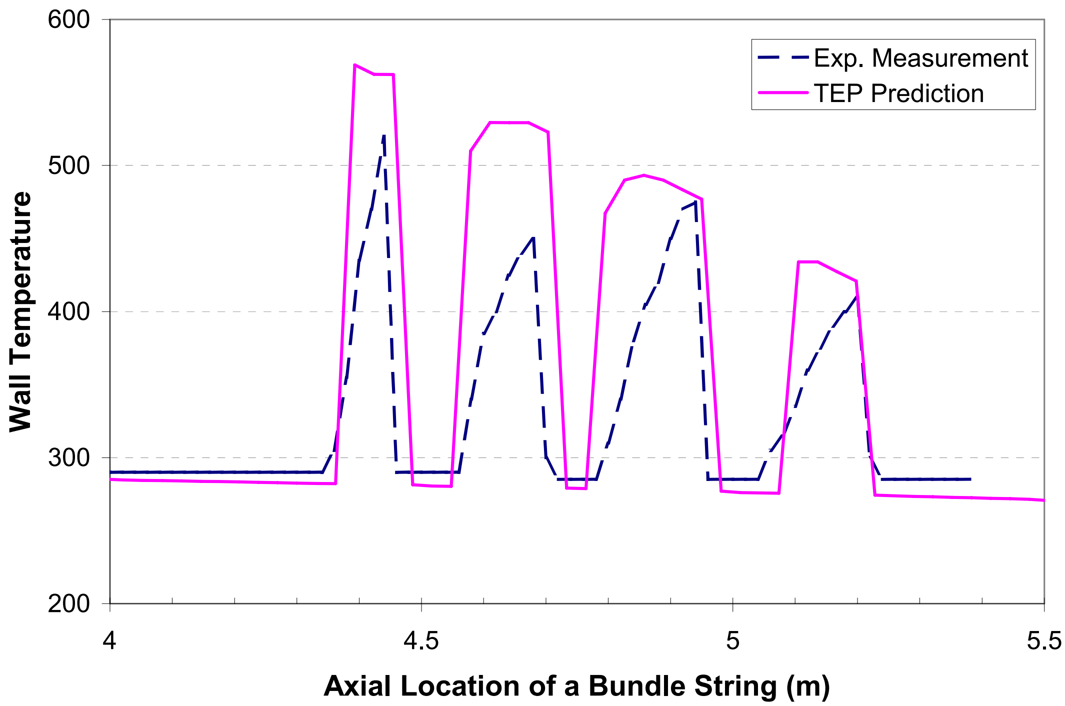

Figure 1 An Example of Validation Results of TEP V3.3 (System Calculations)

6. References

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