Heat Transfer Regime Calibration for Phase-change Heat Exchangers in RELAP5-3D

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Abstract

The application of large thermal-hydraulic systems codes such a RELAP5-3D for design of nuclear power plants, including safety analysis, requires accurate characterization of the fluid flow field and thermal distribution inside a heat exchanger. As is common with these codes, a heat exchanger is modeled using control volume and heat structure building blocks, conforming to rigid conventions and solution techniques. As part of the design effort ongoing for the B&W mPower™ small modular reactor, RELAP5-3D's regime-dependent heat transfer boundary condition model, a twenty-word formatted option for describing local characteristics influencing a heat structure's boundary condition, has been completed. This paper describes this feature and presents a technique for using these modeling parameters to calibrate a phase-change heat exchanger, such as a steam generator, to match a known performance target.

Keywords: steam generator, heat transfer, RELAP5-3D

Introduction

Phase-change heat exchangers for steam generation or condensation is a commonly used technology for industrial applications and, in particular, in pressurized water reactors (PWRs) supplied by Babcock and Wilcox (B&W) and others. Since the safety analysis of PWRs is strongly influenced by steam generator heat transfer performance, a considerable effort is afforded to the testing and simulation of the steam generator through the range of anticipated operation. Whereas the traditional approach by safety analysts to analytically model steam generator performance involves the development of empirical correlations from test data, B&W mPower has pursued a generic "experientially-informed" phenomenological approach. The benefit of that approach relates to its implementation into B&W mPower's proprietary version of the RELAP5-3D thermal-hydraulics safety analysis code (Reference 1).

The principal challenge of modeling phase-change heat exchanger phenomena with RELAP5-3D relates to model approximations from a stream-tube finite volume modeling scheme and the liquid-vapor topology along the length of the heat exchanger. Beyond the numerical modeling challenges, physically the heat transfer rate in a phase-change heat exchanger is tightly coupled to pressure and the boiler/condenser liquid fraction. To compensate for minor inaccuracies, analysts modeling phase-change heat exchangers will adjust backpressure and feed flow within their nominal uncertainty range to align the model with data. Should that be unsuccessful, analysts often resort to calibrating the secondary side heat structure pitch-to-hydraulic-diameter ratio or fouling factor.

Releases of RELAP5-3D prior to the latest publically available version (v4.0.3) have included an incomplete implementation of an optional regime-dependent heat transfer boundary condition model allowing the user to selectively bias critical heat flux (CHF), transition boiling, and film boiling heat transfer. B&W mPower has sponsored an extension of that model and RELAP5-3D users can now calibrate heat transfer coefficients related to nucleate boiling, which are laminar- and turbulent- forced convection, free (natural) convection, and nucleate boiling.

Essential to the calibration process is an evaluation method true to the "top-down, bottom-up" philosophy. As a sample problem, a simple counter-current, flat plate heat exchanger configuration is used as a demonstration, where a figure-of-merit, exit vapor temperature, has been quantified against an uncertainty domain defined by the set independent heat transfer regime multiplier available in RELAP5-3D. Using RELAP5-3D as the simulation engine, the figure-of-merit range was populated from 100 calculations derived from a statistical sampling on the set of new heat transfer regime multipliers. Using an ANalysis Of VAriance (ANOVA) method, sensitivity measures informing the calibration effort are derived.

Heat Transfer Modeling in RELAP5-3D

The physical process of a heat exchanger consists of distributed parameter dynamic elements, mathematically represented by nonlinear partial differential equations with the independent variables being time and space. In RELAP5-3D these equations are simplified into a differential stream tube form with time- and volume-average dependent variables and are well described in References 2 and 3. Conceptionally, the general mathematical scheme (nodalization) for a heat exchanger appears in Figure 1.

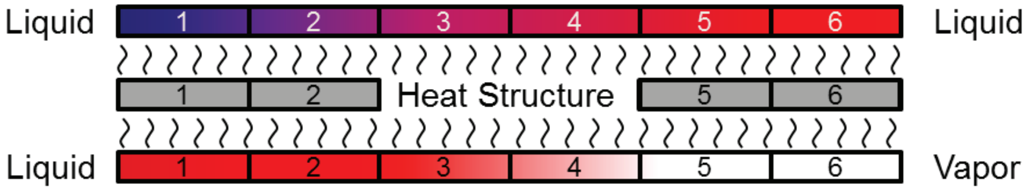

Figure 1 Standard modeling for counter-flow heat exchanger in RELAP5-3D

In RELAP5-3D the user specifies model parameters that describe the finite volumes for flow coupled by one-dimensional conduction, commonly through a plate (Cartesian) or tube (cylindrical) model (i.e., the heat structure). Heat transfer at the surfaces of the structural interface is the consequence of forced and/or natural convection, which is a function of both the magnitude and direction of flow in the heat exchanger.

RELAP5-3D provides various options for describing local characteristics influencing a heat structure's fluid boundary condition. The default model, described by nine model parameters (i.e., "nine-word model"), is applicable in most cases. The most basic implementation of this model is defined by the heated-hydraulic diameter with default values for the remaining words. If set to 0.0, the hydraulic diameter for heat transfer computation defaults to the hydrodynamic volume value. For the steam generator tubes, the twelve-word option is necessary to define the pitch-to-diameter and, optionally, a fouling factor.

In 2007, a project was initiated at the Idaho National Laboratory, principal developers of RELAP5-3D, to include a regime-dependent heat transfer boundary condition model that includes heat transfer multipliers specific to particular heat transfer regimes. While the RELAP5-3D Users Manual describes these multipliers, the set of multipliers were only partially implemented. It has since been expanded through the sponsorship of B&W mPower. to facilitate modeling the B&W mPower small modular reactor.

Computation of Heat Fluxes in RELAP5-3D

Heat flux is computed as a heat transfer coefficient multiplied by a temperature difference. The temperature difference is the difference between the temperature on the surface of the heat structure and the bulk temperature in the fluid adjacent to the heat structure. RELAP5-3D's heat transfer package partitions the total heat flux at the surface of a heat structure into heat fluxes from or to the liquid and vapor/gas phases. For a single constituent (e.g., no noncondensible gas), the heat fluxes are defined using four heat transfer coefficients and four fluid/saturation temperatures, as given by

$$q''_{w,f} = h_{w,f}\left(T_w - T_f\right) + h_{w,sat}(T_w - T_{sat}) \tag{1}$$

$$q''_{w,g} = h_{w,g}\left(T_w - T_g\right) + h_{w,sat}(T_w - T_{sat}) \tag{2}$$

$$q''_{w,T} = q''_{w,f} + q''_{w,g} \tag{3}$$

where $q''_{w,f}$, $q''_{w,g}$ and $q''_{w,T}$ are the liquid, vapor, and total heat flux, respectively; T_w, T_f, T_g, and T_{sat} are wall, liquid, vapor, and saturation temperature, respectively; and $h_{w,f}$, $h_{w,g}$ and $h_{w,sat}$ are liquid, vapor, and saturation heat transfer coefficients, respectively.

Modeling phase-change using the discretization assumed in RELAP5-3D requires a suite of correlations describing the complete spectrum of heat transfer phenomena experienced on both sides of the structural interface. For example, on the boiler side of a typical once-through steam generator, heat transfer begins as subcooled liquid. As the flow progresses through the heat exchanger, the liquid is then saturated and boiled away. Droplets appearing in the fluid downstream of the crisis point vaporize before reaching the exit. At the exit the steam is significantly superheated.

Heat transfer from the conductive surfaces to water/steam is empirically modeled from one of several correlations appearing in RELAP5-3D's heat transfer package. Selection of a particular correlation is dependent on the heat transfer regime (e.g., nucleate boiling, transition boiling, etc.). It also depends on the correlations range of applicability. Given the complexity of the selection logic, it is not repeated here. Generally, RELAP5-3D uses the Chen boiling correlation (Reference 4) up to the critical heat flux (CHF) point. A table lookup method developed by Groeneveld, Cheng, and Doan is used for the prediction of CHF (Reference 5). Nucleate boiling, the focus of the recent extension to the regime-dependent heat transfer boundary condition model, relies on evaluating forced turbulent convection, forced laminar convection, and natural convection and selecting the maximum of these three. The correlations are by Dittus-Boelter, Sellars-Tribus-Klein, and Churchill-Chu, respectively (Reference 6 – 8). Modifications and correlation substitutions are incorporated in RELAP5-3D to address unique geometric configurations appearing in nuclear power plants.

Model Implementation Limits

Experienced RELAP5-3D analysts know well that the difficulty in obtaining satisfactory simulations of heat exchanger performance is partly nodalization dependent. The most obvious difficulty from discretization appears simply with matching steady-state results with data. In addition, transient studies will often show instability when a liquid interface moves across cell boundaries, resulting in discrete jumps in overall heat transfer.

The generic numerical expression solved by RELAP5-3D for heat structure temperatures involves the fluid/saturation temperatures from both a left and right boundary volumes. If only one side of the heat structure is attached to a hydrodynamic volume, that boundary condition involves only those volume conditions. The associated assumptions align well with the numerical approximations in the hydrodynamic solution that assume the conservation equations for each volume include new time values only from that volume. Most heat structures such as fuel pins, plates, or piping have only one side connected to a hydrodynamic volume.

With a heat exchanger, temperatures from more than one volume in the energy equations for each attached volume must be resolved, which is less compatible with RELAP5-3D's hydrodynamic advancement scheme. In the area-integrated form of equations (1) or (2) in RELAP5-3D (i.e., integrated over the surface area of the heat structure in contact with the fluid), the surface temperature is the average surface temperature and the fluid temperature is the average bulk fluid temperature. Consequently, the temperature at the outlet of the volume in the solution of the fluid energy equation is really this average bulk temperature. Effectively, the heat flux underestimates the energy transfer from the heat structure to the fluid, as illustrated in Figure 2 and Figure 3.

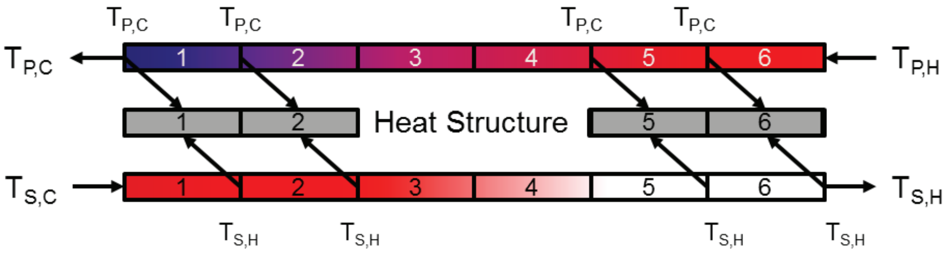

Figure 2 Assignment of temperature boundary condition in RELAP5-3D heat exchanger model

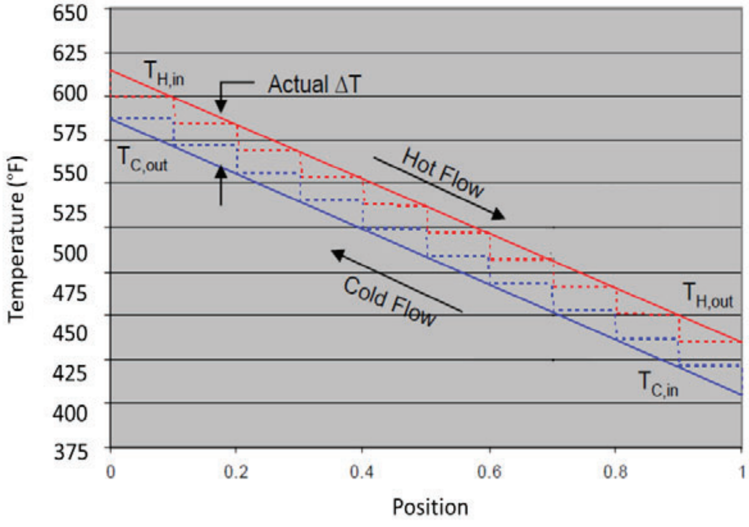

Figure 3 Temperature profile in a heat exchanger model illustrating heat transfer under-prediction

Heat Exchanger Model Compensation Options

The error resulting from the form of the numerical solution is proportional to the length of control volume and the temperature difference across the structural interface. When errors are relatively small, adjustment to pumped flowrates and backpressure within their nominal uncertainty ranges may be sufficient. In the case of a phase-change heat exchanger, heat transfer rates very significantly through the different regimes. By moving the wetwall-to-drywall transition point, heat transfer performance can be calibrated. This is easily done in a steam generator. For example, by increasing feedwater flow will extend the wetted condition along the heat transfer interface; that is, more of the tube surface area experiences the more effective heat transfer from nucleate boiling rather than ineffective heat transfer (convection to steam).

For larger errors the most common solution is to move to finer nodalization. This option has some disadvantages. A large number of control volumes increases problem run time and reduces the material Courant limit. Further, the constitutive package in RELAP5-3D imposes a requirement that the control volume length must exceed its diameter (Reference 9).

One method to reconcile the problem is to stagger the heat structures between control volume centers (Reference 10). This spatially aligns the average bulk fluid temperatures to the heat structures. It does require some model accommodation for the front and back ends of the heat exchanger, which can take several forms. While the implementation of this modeling approach in the RELAP5-3D input is more cumbersome, it is feasible. For single-phase heat exchangers, an option is available for heat structures accommodating the staggered mesh/control volume arrangement without the more cumbersome model (Reference 1, Section 4.11).

The other alternative is to artificially increase heat transfer through the use of a multiplier hard-coded into the program. This can be done simply by increasing the modeled surface area or pitch-to-diameter ratio or by adjusting the fouling factor. Departing from design specification is generally counter to the best-practices. In addition, while steady-state data can be easily applied to calibrate, the technical basis supporting transient performance may be weak.

An advantage of using a multiplier approach is in the characterization of an evaluation methodology that addresses uncertainties of the more important phenomena, which often includes primary-to-secondary heat transfer. In that setting, uncertainties should be examined local to the physical process. When modeling in RELAP5-3D, this is with respect to the specific correlation or correlations describing a particular heat transfer regime.

Regime-Dependent Heat Transfer Boundary Condition Model

General heat structure data are entered on heat structure Card 1CCCGXXX, where CCCG is the heat structure/geometry number and XXX designates one of several parameter sets for either dimensioning the model or describing global and local characteristics. The regime-dependent heat transfer boundary condition model refers to the heat transfer multiplier code input appearing in Cards 1CCCG8XX and 1CCCG9XX. Between an effort originally performed in 2007 at the INL and the recent work supported by B&W mPower, RELAP5-3D now includes input for multipliers on eight heat transfer regimes. These are:

1. free/natural free/natural convection
2. laminar forced convection
3. turbulent convection
4. nucleate boiling
5. critical heat flux (CHF)
6. transition boiling
7. film boiling
8. condensation

The earlier implementation only addressed those for CHF, transition boiling and film boiling, while the recent development covered those related to nucleate boiling, items 1 – 4. A multiplier on condensation heat transfer remains to be addressed. The particular multiplier parameters are available when the "twenty-word" format option is selected (Word 1 = 5 on Card 1CCCG800). The first eleven words of this format are identical to the first eleven words of the twelve-word format, whereas the remainder addresses the regime-dependent information.

For a phase-change heat exchanger, two multipliers can be applied for each heat structure, corresponding to the two structural interface surfaces. Since in most applications only one boundary condition will undergo phase change, adjustment of the single-phase side would likely have less impact on heat transfer performance. As such, it is best-practice to focus the initial adjustment to the phase-change side, followed by the smaller adjustment, if necessary, on the single-phase side

The multipliers are applied independent of each other. Notably, with the modification to the transition boiling it is possible for the modified transition boiling heat flux to be greater that the value of the CHF heat flux. This is an unstable situation. If CHF were to occur, the code forces the heat structure into transition boiling that has a higher heat flux than the CHF heat flux. This could cool the heat structure down enough to revert the heat structure back into nucleate boiling. The structure would likely repeat the sequence, going through CHF into transition boiling again, never to reach film boiling. At this time, no check has been implemented to prevent this scenario.

Code Modifications

The RELAP5-3D subroutines modified to implement this features reside primarily under the heat transfer advancement subroutine HTADV, called by the TRAN subroutine, which is responsible for the overall advancement of the solution. The HTADV subroutine identifies the heat transfer regime then calls the appropriate lower tier heat transfer routine, shown in Figure 4.

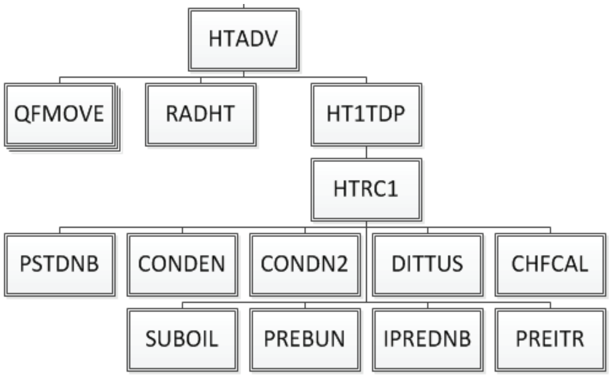

Figure 4 RELAP5-3D Transient/steady-state FORTRAN block purpose

In the original 2007 implementation, the following subroutines and common decks were modified:

- **Subroutine CHFCAL** - modified to multiply the code-computed value of the CHF heat flux by the user input multiplier.
- **Subroutine HTCOND** - modified to store the user input multipliers for either the left side or the right side of the heat structure into a local array for use by the heat transfer coefficient routines.
- **Subroutine HTRC2** - modified to store the user input multipliers for the non-reflood side of the heat structure into a local array for use by the heat transfer coefficient routines.
- **Subroutine PSTDNB** - modified to multiply the computed values of the transition boiling heat transfer coefficients and the film boiling heat transfer coefficients by the appropriate multiplier.
- **Subroutine QFHTRC** - modified to store the user input multipliers for the reflood side of a heat structure into a local array for use by the heat transfer coefficient routines.
- **Subroutine RHTCMP** - modified to read/store user input heat transfer coefficient multipliers.
- **Common HTSRCM** - modified to reserve storage for the user input heat transfer coefficient multipliers for both the left and right sides of a heat structure.
- **Common HTSRCMC** - modified to include a description of the variables added to common deck HTSRCM.
- **Common HTRCOM** - modified to reserve storage for the local copies of the user input heat transfer coefficient multipliers.
- **Common HTRCOMC** - modified to include a description of the variables added to common deck HTRCOM.

While the input processor subroutines were modified in the original implementation to read the multipliers related to nucleate boiling, the heat transfer routines had not been modified to use the user input value. The update prepared by B&W mPower implements only the multipliers related to the calculation of nucleate boiling heat transfer, a multiplier on condensation heat transfer remains to be completed.

For the nucleate boiling multipliers, the code change emphasis was on the DITTUS subroutine. DITTUS is used to compute the value of the macroscopic heat transfer coefficient for the Chen nucleate boiling correlation. It applies the forced convection multiplier, the laminar convection multiplier, or the natural convection multiplier to the heat transfer coefficient computed in DITTUS. The specific code changes were:

- **Subroutine DITTUS** – modified to save the multiplier used for the heat transfer coefficient returned by the routine.
- **Subroutine RHTCMP** – modified to print the correct message if a negative value for the nucleate boiling multiplier was input by the user
- **Module HTRMOD** – modified to save the value of the multiplier computed by DITTUS.
- **Subroutines PREBUN and PREDNB** – modified to remove the effect of the multiplier computed in DITTUS, and then apply the user input nucleate boiling multiplier to both the macroscopic and microscopic parts of the Chen nucleate boiling correlation
- **Subroutine PREITR** – modified to use the nucleate boiling multiplier
- **Subroutine AATL** – modified to print the correct version number and to indicate that updates were applied to the code

Verification Testing

The original 2007 implementation was tested using a modified version of a model of the Oak Ridge National Laboratory (ORNL) Thermal-Hydraulic Test Facility (THTF). The input was modified to execute through input checking because modifications to the CHF, transition boiling and film boiling heat transfer coefficients would change the transient results and a direct comparison of modified and unmodified version of the test case would not verify that the CHF, transition boiling, and film boiling heat transfer coefficients had been changed by the user input factor. This is because the film and transition boiling heat transfer coefficients are functions of the heat structure surface temperature. If the heat transfer coefficient is modified, the surface temperature is affected that in turn results in different heat transfer coefficients during the next time step, etc., changing the transient results in a nonlinear manner. During initialization, the fluid properties are constant and the surface temperature can be held constant by a user option so that the effect of the user input multipliers can be verified. The surface temperature of one of the heat structures was modified so that the initial state was in transition boiling (the unmodified deck has heat structures in nucleate boiling and film boiling).

The test case was executed several times. The first execution of the test case was with the unmodified version of the code. This established the baseline values of the heat transfer coefficients and CHF. The modified code was executed without adding the values of the heat transfer coefficient multipliers to the input deck to verify that the default multipliers (1.0) would be used. Examination of the printed output showed that identical values for the CHF, transition boiling heat transfer coefficient, and film boiling heat transfer coefficient were obtain as compared to the unmodified code. The test case was then repeated with a modified input deck that included the multipliers whose values were 1.0. The results of this test case were identical to the results of the unmodified code. The last execution of the test case used multipliers of 1.1 on the CHF heat flux, 1.2 on the transition boiling heat transfer coefficient, and a value of 1.3 on the film boiling heat transfer coefficient. Examination of the printed output showed that the ratio of the printed values of the CHF computed by the unmodified code and the modified code was a ratio of 1.1 corresponding to the user input value of 1.1. Similar comparisons for the transition boiling heat transfer coefficient and the film boiling heat transfer coefficient (as well as the corresponding surface heat fluxes) showed that the ratio of the printed values computed by the unmodified and modified versions of the code corresponded to the user input multipliers, i.e., a value of 1.2 for the transition boiling heat transfer coefficient and a value of 1.3 for the film boiling heat transfer coefficient. Finally, all of the installation test cases were executed successfully using the modified code. These results verify that the multipliers have been implemented correctly in the modified code and that the multipliers produce the expected effect on the CHF heat flux and the transition boiling and film boiling heat transfer coefficients.

Evaluation Model Calibration using Uncertainty Analysis

As noted previously, an application for this feature is for evaluation model calibration. As a demonstration, a simple sample problem was created working from the ORNL THTF model. This problem was modified to appear as a phase-change heat exchanger, modifying the heater rod to a flat plate exposed to a hot fluid stream serving as the primary-side of the heat exchanger as illustrated in Figure 5.

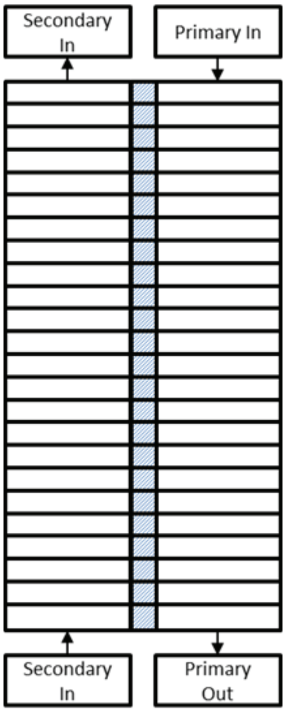

Figure 5 Phase-change heat exchanger model

The calibration exercise seeks to quantify sensitivity between a figure-of-merit and model input using data generated from an uncertainty analysis. The method for generating the data and subsequently evaluating sensitivity is described in References 11 and 12. For the phase-change heat exchanger, performance metrics associated with the identified figure-of-merit, exit vapor temperature were evaluated against the uncertainty estimates for heat transfer regimes appearing in Table 1. Among the model parameters sampled are the fouling factors on both the primary and secondary sides. These parameters are effectively a multiplier on heat transfer applied uniformly along the structural interface. In addition, the multiplier on nucleate boiling is effectively a multiplier on the dominant heat transfer regime among its constituents, laminar-forced convection, turbulent-forced convection, and free convection. Typical of most steam generators, this is turbulent-forced convection.

Table 1 Sample Problem Uncertainty Parameters

Parameter of Interest	**Distribution Type**	**Characterization**
Nucleate Boiling	Normal	$\mu=1.0$, $\sigma=20\%$
Turbulent Forced Convection	Normal	$\mu=1.0$, $\sigma=20\%$
Critical Heat Flux	Normal	$\mu=1.0$, $\sigma=20\%$
Transition Boiling	Normal	$\mu=1.0$, $\sigma=20\%$
Film Boiling	Normal	$\mu=1.0$, $\sigma=20\%$
Natural Convection	Normal	$\mu=1.0$, $\sigma=20\%$
Laminar Forced Convection	Normal	$\mu=1.0$, $\sigma=20\%$
Fouling factor-SS	Uniform	a=0.5, b=1.2
Fouling factor-PS	Uniform	a=0.5, b=1.2

The method for convolving this uncertainty domain followed the procedure now common with best-estimate-plus-uncertainty safety analysis, relying on a "Monte-Carlo"-like nonparametric statistical approach. For each analysis calculation, each of the uncertainty parameters being treated statistically was randomly sampled based on the given probability distribution. Each sample code calculation can be viewed as the performance of an experiment with the experimental parameters being the important phenomena and plant process parameters and the result being any appropriately represented performance metric (i.e., based on correlation with uncertainty parameters).

Based on the results of a suite of 100 sample calculations, the uncertainty range of exit vapor temperature was quantified. The selection of 100 samples is based on the work of Wilks for defining tolerance regions (References 11 and 13). Following this nonparametric statistical approach, when 100 observations are drawn from an arbitrary, random distribution of outcomes, it can be shown that the largest value is such that with 97 percent confidence, at least 95 percent of all possible observations from that distribution will be less than the resulting largest value; that is, this result is the 97/95 tolerance limit. For this application, this 97/95 benchmark is assumed to be a sufficient estimation of the total tolerance limit for characterizing the dominant heat transfer regimes.

To quantify the degree to which a model input parameter affects a model output variable, several approaches are available (References 13). Variance-based methods (i.e., ANOVA) are well suited for accompanying nonparametric best-estimate-plus- uncertainty analysis. Variance-based "importance" analysis is performed by first describing the variance in figures-of-merit in terms of the important model parameters. Using the data from the uncertainty analysis, the set of the more sensitive model inputs are identified through a stepwise multiple regression exercise. The relevance of this understanding is that improved resolution of importance serves to inform the calibration. From the uncertainty analysis results in the heat exchanger sample problem, the correlation and an importance model were characterized relative to the figure-of-merit results and the sampled model parameter values.

The results derived appear in Table 2. The first entry in this table is the identification of exit vapor temperature as the figure-of-merit followed by the standard deviation of the 100 steady-state calculation samples appearing in the last column. Associated with the important model parameters (2nd column) are the sample correlation coefficient (3rd column) and the derived standard deviation on the exit vapor temperature estimate relative to that particular model parameter (4th column). The last column reports the standard deviation of the remainder, which is a measure of the influence of unidentified model and code parameters (i.e., general variability). Once the useful information available in results data is exhausted, the completeness of this procedure is measured. This is the "Ratio of Estimate to Actual," the ratio of the square-root of the sum of the variances (squares of the standard deviation, aka "Convolution of Important Contributors") and the variance of the original exit vapor temperature results).

The derived exit vapor temperature sensitivity to heat transfer performance had a standard deviation (σ) of about 2.5 ˚F (mean, η, of 630.3 ˚F). The dominant model parameter is the secondary-side fouling factor, based on the correlation calculation. Each sample correlation is approximate, based on the comparisons between the independent variables (i.e., sampled model parameters) and the dependent variable (i.e., figure-of-merit). The sign of the sample correlation is noteworthy in that it indicates whether the model parameter is directly or inversely related to the analysis output measure of interest.

Following the secondary-side fouling factor, the next two important model parameters are nucleate boiling and turbulent-forced convection. Notably, the fouling factor globally impacts the length of the heat exchanger and nucleate boiling is dominated by turbulent-forced convection. For this sample problem, the exit vapor temperature uncertainty is reported as 2.468. The convolution of the identified important parameters is 2.443, demonstrating that the combination of the four model parameters provides approximately 99.0% of the influence on the figure-of-merit. These results are shown on separate lines in Table 2 Correlation and Importance Results Summary. Figure 6 and Figure 7 illustrate the trend between exit temperature, the secondary-side fouling factor (actual temperature) and the turbulent forced convection (relative to the mean), which is useful for calibration. Similar trends can be generated for the other model parameters.

Table 2 Correlation and Importance Results Summary

Figure of Merit	Variable name	Correlation	STD from Contributor	STD of Remainder
Exit Vapor Temperature (η = 630.3 ˚F)				2.468
Exit Vapor Temperature	Fouling factor-SS	0.869	2.252	1.01
Exit Vapor Temperature	Nucleate Boiling	0.536	0.541	0.853
Exit Vapor Temperature	Turbulent Forced Convection	0.614	0.524	0.673
Exit Vapor Temperature	Fouling factor-PS	0.843	0.575	0.35
Convolution of Important Contributors		2.443		
Ratio of Estimate to Actual		0.990		

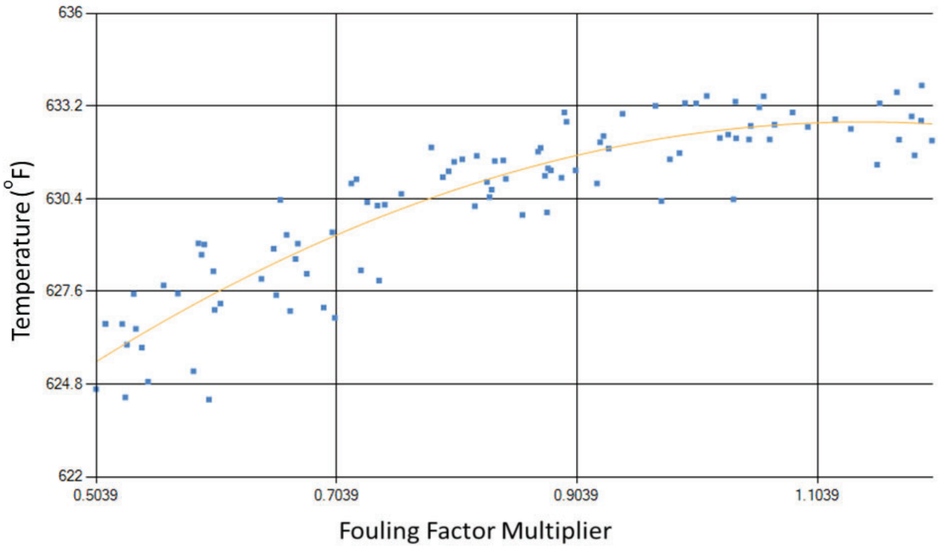

Figure 6 Exit temperature vs. fouling factor multiplier

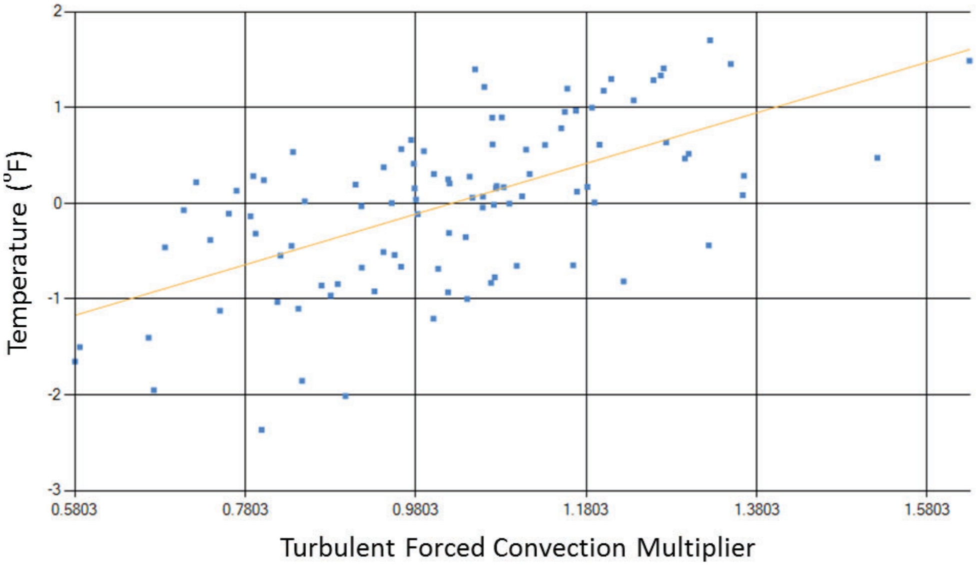

Figure 7 Exit temperature vs. turbulent forced convection multiplier

Conclusions

Heat transfer modeling in RELAP5-3D has known limitations that result in an underestimation of heat transfer, particular when modeling heat exchangers. This paper has presented a regime-dependent heat transfer boundary condition model, which can be used to calibrate a model to a desired target condition. Further, this model is valuable for characterizing an evaluation methodology bias to account for the combination of code and component uncertainties. Using uncertainty and sensitivity methods now common with best-estimate-plus-uncertainty safety analysis applications, a sample problem has been presented illustrating the how the regime-dependent heat transfer boundary condition model could be used for this purpose. The RELAP5-3D code development team at the INL is considering a similar implementation for the broader user community.

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