TITLE: A Comprehensive, Mechanistic Heat Transfer Modeling Package for Dispersed
Flow Film Boiling – Part 2 – Implementation and Assessment

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No. of Tables = 2

1. INTRODUCTION

A comprehensive, mechanistic DFFB heat transfer package has been developed¹ (as was detailed in Part 1 of this paper) for use within nuclear reactor safety analysis codes. The proposed model improves upon previous DFFB models by correcting prior modeling deficiencies and implements a number of novel developments. Some of the advances in the proposed model over previous models include: the implementation of a physically based, subscale Lagrangian trajectory calculation to determine if a droplet can intermittently contact the wall, dry contact heat transfer has been physically linked to the local conditions (i.e., vapor mass flux, wall superheat, entrained droplet fraction, and vapor superheat), a droplet size distribution has been included across all of the calculations, and the inclusion of a novel, two-phase convective enhancement factor.

The proposed modeling package was developed to balance the required computational effort with the accuracy needed in predicting DFFB heat transfer for postulated accidents such as a Loss of Coolant Accident (LOCA). The DFFB model has been implemented within the existing framework of the COBRA-IE computer code. Specifics on the implementation and an assessment of the proposed model are the topics of this paper.

2. COBRA-TF IMPLEMENTATION

2.1 CALCULATION LOGIC PATH

The proposed DFFB model was implemented within COBRA-IE as a standalone module. When called from the heat transfer logic, the DFFB model is provided the local conditions (i.e., pressure, vapor mass flux, wall temperature, and vapor temperature) in addition to geometric parameters which include the hydraulic diameter, the heat transfer area, and the volume of the connected fluid node. Upon receiving the local parameters, a number of preliminary calculations are performed including property lookups, discretization of the droplet distribution, and calculation of the characteristic diameters. Next, the dry contact, radiative, and interfacial heat transfer components are calculated along with the convective enhancement factors for each characteristic diameter droplet. Finally, the bulk convective heat transfer is calculated before calculating effective heat transfer coefficients. **Error! Reference source not found.** summarizes the logic path for the DFFB heat transfer calculation.

In order to implement the proposed DFFB model within the existing COBRA-IE framework, “effective” heat transfer coefficients were utilized. These heat transfer coefficients simply serve as a means of preserving the total heat fluxes from the wall to both the vapor and liquid components and the interfacial heat transfer. Equation (1) gives the effective heat transfer coefficient for the wall to vapor heat transfer which consists of both the bulk convection and radiative components.

$$h_{eff,wv} = \frac{q''_{wv,conv} + q''_{wv,rad}}{T_w - T_v} \quad (1)$$

The wall to liquid heat transfer is segregated in COBRA-IE based upon if it directly results in a change in latent or sensible heat. For heat transfer resulting in changes in sensible heat, Equation (2) gives the effective heat transfer coefficient which consists of only the radiative component.

$$h_{eff,wl} = \frac{q''_{wl,rad}}{T_w - T_l} \quad (2)$$

For changes in latent heat, Equation (3) gives the effective heat transfer coefficient which consists of the dry contact heat flux divided by the local wall superheat.

$$h_{eff,wb} = \frac{q''_{wl,dc}}{T_w - T_{sat}} \quad (3)$$

For the interfacial heat transfer, COBRA-IE utilizes the product of the heat transfer coefficient and the interfacial area (hA). For this case, the total heat transfer rate from the convective and radiative components is divided by the local vapor superheat as given by Equation (4).

$$hA_{vl} = \frac{q_{vl,conv} + q_{vl,rad}}{T_v - T_{sat}} \quad (4)$$

2.2 SENSITIVITY STUDIES

Following the implementation of the proposed DFFB model, a number of sensitivity studies were performed. They included studies to determine the appropriate

discretization of the droplet size distribution and to demonstrate the appropriateness of the assumptions associated with the use of quasi-static subscale Lagrangian trajectory calculation within COBRA-IE. These studies will be detailed in the following subsections.

2.2.1 DROPLET SIZE DISCRETIZATION

The effect of the number of droplet bins on the results of the various DFFB heat transfer contributions was examined such that an appropriate number of droplet bins could be selected. This study examines the inherent trade off between the accuracy of using a large number of bins to describe the distribution and the associated computational resources. Sensitivities were conducted with 1, 2, 3, 5, 8, 10, 15, 25, and 50 bins. **Error! Reference source not found.** summarizes the sensitivity of the dry contact heat transfer component to the number of droplet bins for various wall superheats at atmospheric pressure where dry contact heat transfer can readily be achieved. As the number of bins is increased, the accuracy of the dry contact heat flux modeling is increased. The step-wise decrease observed illustrates the superheats at which a given bin can no longer achieve contact with the wall. Similar sensitivity studies were conducted for various vapor mass fluxes and pressures. All of the calculations showed similar reductions in error with finer discretization of the droplet size distribution as presented in **Error! Reference source not found..**

In addition to the dry contact heat flux, the convective enhancement factor was also found to be influenced by the number of droplet bins. **Error! Reference source not found.** illustrates the sensitivity as a function of wall superheat. Overall, the

convective enhancement factor decreases as the number of droplet bins is increased which can be attributed to more accurate trajectories across the droplet size spectrum. When fewer bins are utilized, the resulting characteristic diameters are larger leading to trajectories which penetrate further into the boundary layer than some of the smaller droplets in the bin.

Additional bin sensitivities were performed for the radiative and interfacial heat transfer components. Very little sensitivity was observed to the number of droplet bins for these heat transfer mechanisms. The use of 1, 2, and 3 bins was found to not accurately capture the effect of the droplet size spectrum while the use of either 8 or more bins required more computational effort than could be justified by the associated gains in accuracy. As such, five bins were selected for the COBRA-IE implementation.

2.2.2 LAGRANGIAN SUBSCALE SENSITIVITY

Appropriateness of the quasi-static, Lagrangian subscale trajectory calculations within COBRA-IE was demonstrated with two independent studies. First, the axial distance travelled by a droplet in the boundary layer compared to the axial height of a typical COBRA-IE node. Second, the time spent in the boundary layer compared to the time step size of COBRA-IE. To perform these studies, trajectory calculations for several thousand combinations of pressure, wall superheat, mass flux, vapor superheat, and entrained fractions were conducted over a wide range of conditions typical of DFFB utilizing five droplet bins. **Error! Reference source not found.** gives the cumulative distribution function (CDF) of the axial distance travelled by the droplets in the boundary layer. It shows that 95% of the droplets travel less than five centimeters axially while

they are in the boundary layer. For comparison, a typical cell length for a reactor safety code is typically on the order of 10-55 centimeters. Thus, the use of Lagrangian subscale trajectory calculations within a COBRA-IE node is acceptable without needing to track droplet trajectories across axial node boundaries. In terms of the time the droplets spend in the boundary layer, **Error! Reference source not found.** gives the resulting CDF. It was observed from the analytical calculations that 95% of the droplets spend less than 3 milliseconds in the boundary layer with over 50% spending less than 0.2 milliseconds. These timeframes are on the order of or close to the typical time step utilized in reactor safety analyses when DFFB phenomenon is present. Thus, the Lagrangian subscale calculations can be performed in a quasi-static manner without the need to track droplet positions between computational time steps.

3. ASSESSMENT OF PROPOSED MODEL

3.1 ASSESSMENT DATABASE

The proposed DFFB heat transfer package was assessed against four sets of experimental data. The assessment focused on steam-water experimental data in vertical tubes. The choice to only examine steam-water data was made given that the model was specifically developed for use in light water reactor safety analysis codes. Additionally, the use of only vertical tube experiments rather than including rod bundle experiments was made to provide a baseline without examining the numerous effects of spacer grids on DFFB heat transfer. These include their effect on the droplet size spectrum and the ability of spacer grids to quench in advance of the quench front and

de-superheat the surrounding vapor. The extension of this model to include the effect of spacer grids is not included in this paper.

The conditions of the tube data utilized in the assessment database are outlined in **Error! Reference source not found.** A total of 118 steady-state experimental runs were utilized in this assessment. The Royal Institute of Technology (RIT)², Bennett³, and CISE⁴ experiments were all uniformly heated while the Harwell⁵ experiments utilized a cosine power shape.

3.2 COMPARISON BASIS

The proposed DFFB heat transfer package assessment results were compared to the results of a version of COBRA-IE that utilized the previous DFFB model. In the baseline version of COBRA-IE, the DFFB heat transfer package utilizes the dry contact model of Forslund and Rohsenow⁶, the radiative heat transfer model of Sun *et al.*⁷, and the convective heat transfer model of Gnielinski⁸. All of the calculations performed in the base version of COBRA-IE utilized the Sauter-mean diameter predicted by the code without a droplet size distribution.

3.3 SAMPLE ASSESSMENT RESULTS

Error! Reference source not found. gives sample assessments from the RIT experiments. As the upper, left plot illustrates, the proposed DFFB heat transfer model gives a marked improvement in the predicted wall temperatures. This is especially true

at the dryout point where the proposed model follows the same axial trend as the experimental data. The over prediction of dry contact heat transfer by the Forslund and Rohsenow⁶ model causes the base results to deviate from the experimental data once the critical heat flux (CHF) is exceeded. The upper, right plot also shows a similar improvement as the temperature profile is predicted better in the vicinity of the dryout point. The lower, left plot illustrates a case in which COBRA-IE does not predict the CHF point correctly. In spite of this, the proposed model still predicts the same temperature trend as seen in the experimental data. This case highlights the importance of correctly predicting the onset of post-CHF heat transfer as well as the local conditions given that both serve as boundary conditions to the DFFB heat transfer model. An additional comparison is given in the lower, right plot in which both the trend and magnitude of the temperature profile are captured. Comparing the top, left and bottom, right figures we can see that the new model was able to improve predictions in cases both where the previous model overestimated and underestimated the heat transfer. This highlights the inadequacy of some of the simplifying assumptions used in the development of the Forslund and Rohsenow⁶ correlation as applied to reactor safety analysis scenarios specifically with respect to the dry contact heat transfer.

A significant improvement in accuracy (shown in **Error! Reference source not found.**) was seen comparing the results from the proposed model over all of the RIT assessment cases for all axial locations for which both the experimental data and predictions were identified as being in DFFB. Using the proposed DFFB model the mean error was changed from 20.64 K to -20.58 K. The root mean square (RMS) error was reduced from 84.66K to 45.90 K. Additionally, the standard deviation was reduced from 82.16 K to 41.05 K. These results illustrate a significant improvement over the

base modeling techniques while replacing an empirical model with a mechanistically based model. The ability of the proposed DFFB model to nearly cut the standard deviation of the error distribution in half demonstrates the advantages of the proposed DFFB model over the base package.

Error! Reference source not found. compares the predicted to measured wall superheats for both DFFB models. As the plot illustrates, the proposed DFFB model closely matches the experimental data both in terms of the magnitude and the ability of the model to match the slope of the experimental data. The previous model provided a clear trend that would over predict the wall superheat with increasing measured wall superheat. The new model does not exhibit this non-physical trend.

Error! Reference source not found. illustrates sample results from the Bennett series of the assessment. Similar improvements were seen with the proposed DFFB model with the Bennett experiments. The upper, left plot shows that in situations where the previous model accurately predicted the heat transfer, the new model also provides accurate predictions of the wall temperature. In the upper, right plot, an improved prediction of the wall temperature profile with the proposed model is seen. The bottom two plots of **Error! Reference source not found.** provide additional comparisons in which the proposed DFFB model improved the prediction of the axial wall temperature profile.

Comparing the results for all of the Bennett tube experiments, improvements in both the mean and standard deviation of the errors are seen with the proposed DFFB model as shown in **Error! Reference source not found.**. Using the proposed model, the mean error was reduced to 5.32 K from the original of 43.46 K. Similarly, the RMS

error was reduced from 96.41 K to 46.34 K. The proposed DFFB model was also more precise as the standard deviation was reduced from 86.15 K to 46.07 K.

Error! Reference source not found. provides additional assessment results from the Harwell and CISE experiments. Similar improvements are seen with the use of the proposed DFFB model over the base line model of COBRA-IE. For the Harwell series, the proposed DFFB model reduced the overall mean error from -32.90 K to -15.26 K. The RMS error was changed from 41.43 K to 44.74 K with the proposed model. For the CISE series, the overall mean error changed from 27.50 K to -49.80 K while the RMS error was reduced from 64.82 K to 55.55 K. Additionally, the standard deviation was also reduced from 58.94 K to 24.71 K for the CISE series.

3.4 OVERALL ASSESSMENT RESULTS

The resulting errors from the assessment were examined for any biases based upon the local conditions as well as the fraction of the heat transfer attributed to each DFFB heat transfer component. No large biases were observed with the proposed DFFB model¹. Overall, the assessment included data from four separate experimental facilities with a total of 118 experimental runs. **Error! Reference source not found.** compares the resulting wall temperature errors for both DFFB models across all of the experimental data. Overall, the proposed DFFB model reduced the mean error from 27.36 K to -14.27 K while almost cutting the standard deviation in half from 82.15 K to 44.75 K. Additionally, the RMS error was reduced from 86.56 K to 46.96 K across all of the experimental data points. The significant reductions in both the RMS error and standard deviation can also be seen in **Error! Reference source not found.** as the proposed DFFB model results on the left hand side are much closer to the forty five

degree line and have significantly less scatter. Additionally, the trend of over predicting wall superheats as the measured wall superheat increases has been removed with the proposed model.

Error! Reference source not found. summaries the provided by the proposed model over the baseline model based upon Forslund and Rohsenow⁶. The proposed DFFB model changed the mean error by 41.63 K and reduced the RMS error by 39.60 K. The predictions of the proposed DFFB model are also more precise as the standard deviation was decreased by 37.40 K. The reduction in the data scatter can also be seen in the ranges of the data. The proposed model reduced the range containing 90% of the data by 135 K and 95% of the data by 170 K. Overall, significant improvements by the proposed model have been demonstrated over a wide set of experimental tests and conditions.

3.5 IMPACT ON EXECUTION TIME

The impact of the proposed DFFB heat transfer package on the execution time of COBRA-IE was examined. The total execution time of each of the 118 assessment cases was compared between the two different DFFB heat transfer packages. On average, the execution time was increased by 40%. Despite the increased execution time, it should be noted that a number of the predictions of the proposed DFFB model remained in post-CHF regimes much longer than the baseline version which tends to skew the results in addition to the fact that the assessment basis only consists of problems in which the proposed model would be exercised heavily. Thus, it has been concluded that the significant improvements seen with the proposed DFFB heat transfer package far outweigh the associated increase in execution time.

4. CONCLUSIONS

A comprehensive, mechanistic DFFB heat transfer package has been developed and implemented within the existing framework of COBRA-IE. The proposed model includes several novel advances over previous DFFB models while balancing the accuracy required for DFFB predictions and the computational effort. The different modeling assumptions inherent in the model have been demonstrated as appropriate through the use of sensitivity studies. The proposed model has been assessed against experimental data from four separate facilities. A total of 118 experimental runs, spanning a wide range of mass flux, pressure, quality, wall superheat and heat flux have been examined. Significant improvements have been seen in the predicted wall temperatures as the mean error, RMS error, and standard deviations have all been reduced. Additionally, the shortcomings of the empirical models typically used in reactor safety codes have been clearly identified. These results provided by the new model provide evidence for its superior accuracy relative to that of traditional models.

4. ACKNOWLEDGEMENT

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NOMENCLATURE

General

A_{int}	Interfacial area [m ²]
h	Heat transfer coefficient [W/m ² -K]
q	Heat transfer rate [W]
q''	Heat flux [W/m ²]
T	Temperature [K]
T_{sat}	Saturation temperature [K]

Subscripts

b	Boiling
$conv$	Convective
dc	Dry contact
l	Liquid
rad	Radiative
v	Vapor
w	Wall

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TABLES

	RIT	Bennett	Harwell	CISE
Number of Runs	25	19/56	9	9
Inner Diameter (mm)	14.9	12.6	12.7	12
Length (m)	7	3.66 / 5.56	3.66	2
Power Shape	Uniform	Uniform	Cosine	Uniform
Pressures (MPa)	3.0-14.0	6.89	6.89	1.5-9.0
Mass Flux (kg/m²-s)	496-1990	380-5235	720-4060	255-1505
Inlet Temperature (K)	496-600	523-550	538-547	-
Inlet Quality (%)	-	-	-	0.32-0.86
Wall Heat Flux (kW/m²)	405-1053	362-2082	826-1527	262-1014

Assessment Database Conditions

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Table 1

Parameter	Proposed	Original	Change
Mean Error	-14.27 K	27.36 K	-41.63 K
RMS Error	46.96 K	86.56 K	-39.60 K
Standard Deviation	44.75 K	82.15 K	-37.40 K
90 % Interval	-76 K to 60 K	-95 K to 176 K	- 135 K
95 % Interval	-85 K to 86 K	-110 K to 231 K	- 170 K

DFFB Model Comparison Summary

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Table 2

FIGURES

DFFB Heat Transfer Logic Path

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Figure 1

Dry Contact Bin Sensitivity for Various Wall Superheats

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Figure 2

Convective Enhancement Factor Bin Sensitivity for Various Wall Superheats

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Figure 3

CDF of Axial Distance Traveled

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Figure 4

CDF of Time Spent in the Boundary Layer

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Figure 5

Example RIT Assessments

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Figure 6

Histogram Comparing Wall Temperature Errors for the RIT Tube Experiments

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Figure 7

Comparison of Predicted to Measured Wall Superheats for RIT Tube Experiments

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Figure 8

Example Bennett Assessments

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Figure 9

Histogram Comparing Wall Temperature Errors for the Bennett Tube Experiments

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Figure 10

Example Harwell and CISE Assessments

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Figure 11

Histogram Comparing Wall Temperature Errors for All Tube Experiments

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Figure 12

Comparison of Predicted to Measured Wall Superheats for All Tube Experiments

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Figure 13