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Assessment of COBRA-TF for Critical Heat Flux

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Abstract

COBRA-TF is a two fluid , three field subchannel code. Three fields are continuous vapor, continuous liquid and droplet. Some assessments are conducted to validate the related models and to estimate a code ability through dryout and post-CHF experiment in a tube and DNB test in rod bundles. It turned out form dryout and post-CHF experiment that the predicted dryout locations and wall temperature profiles are in close agreement with the experiments. On the other hand, DNB prediction of COBRA-TF are performed for two kinds of rod bundles along with EPRI CHF correlation. To estimate its performance COBRA-IV of homogeneous model is also run for the same data. The results say that COBRA-TF/EPRI is better in DNB prediction than COBRA-IV/EPRI. In addition the thermal-hydraulic behaviors due to the different two-phase flow models are presented at the condition of CHF.

I. Introduction

COBRA-TF[1] is a thermal-hydraulic subchannel code. It provides a two-fluid, three field representation of two phase flow, instead of the homogeneous representation used in the previous versions of COBRA series. Three fields are the continuous liquid, continuous vapor and entrained liquid drop. Dividing the liquid phase into two fields is the reasonable way of handling flows where the liquid can appear in both film and droplet form. So this code is formulated suitable for the prediction of dry-out in a channel and in rod bundles. Even some assessments have been conducted so far for entrainment/ deposition and film dryout phenomena, it's performance is not widely evaluated yet for the various kinds of two-phase experimental data. Departure from Nucleate Boiling (DNB) phenomenon is one of the remaining areas to be examined.

In this study two kinds of data sets are analyzed to assess COBRA-TF. One is the dryout and post-CHF heat transfer experiment in uniformly heated tube. The location of dryout point and the wall temperature profile will be compared in order to evaluate the code ability. The other is DNB test data for rod bundle. For this analysis EPRI CHF correlation[2] is installed in COBRA-TF. The DNB prediction of COBRA-TF/EPRI will be made for axially uniform and non-uniform heat flux cases. On the other hand, regarding to DNB data analysis COBRA-IV of homogeneous model has been widely used over the world and accepted reasonable for the design tool. In order to estimate those performances the results of COBRA-TF/EPRI are compared with that of COBRA-IV/EPRI. In addition the thermal-hydraulic behaviors due to the different two-phase flow models are presented at the condition of CHF.

II. Assessments

1. Dryout Experiment

a. Description of Experiment

Bennett etal.[3] data for dryout and post-CHF heat transfer were used to assess the related models and the code characteristics. The test section is the electrically heated tube with 19 ft long ,0.497 inch inner diameter. The subcooled water at the inlet flows upward at 1000 psia. The dryout point and wall temperature profile were measured in the experiment. Two data of 5359 and 5294 were selected as low and high mass fluxes.

b. Analysis

For the assessment of dryout phenomenon, the physical models related to liquid entrainment/ deposition play a important role in determining the dryout of liquid film. COBRA-TF uses separate models for entrainment and deposition that result in a net entrainment. The entrainment generation rate m_e [4] is basically Sugawar's model, but to reflect the mass flow effect a Reynolds number ratio term is multiplied as follows:

$$m_e = 0.219 \left(\frac{\Delta h_{eq} \tau_i}{\sigma}\right)\left(\frac{U_v \mu_l}{\sigma g}\right)\left(\frac{\rho_l}{\rho_v}\right)^{0.4}\left(\frac{Re_l}{Re_{vl}}\right)^m$$

where Δh_{eq} is the hydrodynamic equivalent wave height ,Re_{vl} is the vapor Reynolds number at the interface between liquid film and vapor and m = 0.235. The exponent m of Reynolds number ratio is correlated to best fit *Hewitt etal.* [5] and *Keeys etal.*[6]data. The deposition rate m_{de} is the same as the Sugawar's model. The dryout point is defined as the disappearance of liquid film on the heated surface. The post-CHF heat transfer model for dispersed flow is a superimposition of the vapor convection (Dittus-Boelter), wall-rod radiation (Sun etal.[7]) and droplet impingement (Forslund-Rohsenow[8]).

c. Results and Discussions

There are two ways to identify the dryout occurrence from the COBRA-TF output. One is a liquid film dryout and the other is a sharp increase of wall temperature. Physically both locations should be closely connected to each other. The predicted dryout positions are compared with the measured one for two cases in Table 1. Figure 1 and 2 represent the axial variations of the continuous liquid void fraction and wall temperature along with the measured data. The results show the consistency of dryout and sharp wall increase. In the case of low mass flux and low heat flux 5359, the entrainment generation is rapidly increased at 10 to 40 inch from the inlet. Beyond the part the liquid film diminishes gradually up to dryout position. COBRA-TF shows the capability to predict the trend that the wall temperature continues to increase above the dryout point as shown in the measured data. In the case of high mass flux and high heat flux 5294 the liquid film is rather gradually decreased up to dryout point. The measured temperature trend which keeps constant for post-dryout region is also simulated properly. Therefore it can be said that COBRA-TF is capable to predict the dryout and post-CHF heat transfer.

2. DNB Test

a. Description of DNB Test

Westinghouse bundle DNB tests[2] were used for the assessment of COBRA-TF. Two rod bundles having 0.422 inch outer diameter were selected. But one has the uniform axial heat flux (TS102) and the other the non uniform axial heat flux (TS110). The radial and axial geometry for test section 102 and 110 are presented in Figure 3 and 4, respectively. The axial heat flux distribution is shown in Figure 5. The ranges of test conditions are described as follows : pressure 1505 to 2157 [psia], mass flux .954 to 3.62 [Mlb/ft^{2}hr], inlet temperature 473. to 603.[°F], heat flux .389 to .894 [MBtu/ft^2 hr].

b. Analysis

As important models for the analysis of thermal-hydraulic behavior in the rod bundle, the turbulent mixing and void drift parameters have to be determined appropriately. The turbulent (eddy diffusivity) mixing takes into account the effect of the stochastic pressure and flow fluctuations while void drift results from the tendency of a two phase flow to approach an equilibrium condition. COBRA-TF input for turbulent mixing and void drift are the mixing coefficient β and equilibrium distribution weighing factor κ, respectively. These values are subject to be evaluated by testing various values for mixing coefficients and finding the values best agreeing with the measured flow and enthalpy distributions at the subchannels under the two-phase flow conditions. But there is no appropriate data available for two phase flow, the recommended TDC of 0.02[2] from single phase mixing test was tried for the analysis of CHF test. It was found unfortunately that COBRA-TF become unstable numerically for the value and finally fail to calculate. It can not accommodate that amount of turbulent mass exchange between subchannels. So some calculations with several combinations of two input values of β, κ were examined for a single CHF test condition. The best combination which gives the MDNBR close to 1.0 will be decided to be used for the analysis. A DNBR is defined as follows :

$$DNBR = q''_{pred} / q''_{meas}$$

where q''_{pred} is the predicted CHF heat flux and q''_{meas} is the local measured heat flux. EPRI correlation is installed in COBRA-TF for the prediction of CHF heat flux in rod bundles. The q''_{pred} is calculated by the EPRI correlation using local flow conditions from subchannel analysis. The q''_{meas} is simply determined from rod power distribution and the measured total bundle power.

COBRA-IV with homogeneous model is widely used and accepted reasonable as far as DNB prediction is concerned. To understand the effect of two phase flow models on DNB COBRA-IV is also run for TS 110 with the recommended TDC value of 0.02. The results are compared between COBRA-IV/EPRI and COBRA-TF/EPRI. In addition the local mass flux and quality variations along the axial distance are also compared at the CHF condition. The calculation domain for the analysis is one of the eighth of rod bundle using the geometrical symmetry.

c. Results and Discussions

i) Sensitivities of Mixing and Void Drift Parameters on DNBR

Six combinations of β and k were examined to see the sensitivities of mixing and void drift parameters on DNBR , based on single test condition of TS110 : Pressure 1505. Psia, inlet temperature 520.°F, mass flux 2.586 Mlb/ft^2hr and measured bundle average heat flux 0.513 $Mbtu/ft^2hr$. It was revealed from the results in Table 2 that the MDNBR decreases as turbulent mixing parameter increases, while MDNBR increases as void drift parameter increase. From the results the sensitivity of turbulent mixing parameter on DNBR is large while that of void drift is relatively small. It means that it is important to determine the turbulent mixing parameter for CHF analysis. In this work, the combination of β= 0.0 and k= 0.0 was selected because the combination results in MDNBR close to 1.0.

ii) Comparisons of Local Conditions between two-fluid model and homogeneous model

The local conditions are determined by the subchannel code and might be different from code to code because the different physical models are embodied to close the equation set for two-phase flow. It is meaningful to compare the local quantities within the bundle between COBRA-TF and COBRA-IV. For the same condition of above i) the mass flux and quality variations along the axial distance are plotted in Figure 6 and 7. As we expect, for the center region of channel 1,2 and 3 the mass flowrates are higher than the side region of channel 4,5,and 6, because of the effect of shroud wall, up to 4.5 ft from the bottom. The position seems that the subcooled boiling just start judging from the quality of -0.5% at the hot channel in Figure 7. The maximum band of mass fluxes between channels is less than 0.3 Mlb/ft^2hr. After that point the mass fluxes in center region become lower than that in the side region because the two phase effect on the hydraulic characteristics become dominant. In general for the single phase flow the local mass distributions in both codes show quite similar results. But in two phase region two codes show the peculiar trends. In the case of COBRA-TF the mass flux of each channel keeps going its way to the exit generally. But in the case of COBRA-IV the mass flux of each channel turns, at some point, the direction and come closer to each other toward the exit. Those turning points are not same for all channels. The turning point of channel 1, hot channel, is faster than any other channel, and coincides with the point of becoming the saturation state (quality $\chi = 0.0$) in Figure 7. This situation is similar to the other channels as well. Thus it may be said that the saturated boiling flow makes the flow distribution flatter in the homogeneous model, while it makes steeper in two fluid model. On the other hand COBRA-IV regards the subcooled condition as no quality while COBRA-IV does not as depicted in Figure 7.

iii) DNB Predictability

The results of the predicted to the measured ratio (P/M) for two test sections are summarized in **Table** 3. The standard deviation of COBRA-TF/EPRI correlation is 0.0577 and the mean is 0.991 for total thirty seven data. The error of P/M due to mass flux, pressure and quality are shown in Figure 8. Even the predictions are slightly underestimated about 1800 psia, the data scattering are generally random around the 1.0. There is no apparent systematic error in the results in Figure 8 b).

The axial heat flux shape effect can be evaluated from the statistics of P/M ratio in Table 3 for the uniform and *usinu* cases. For uniform heat flux, the standard deviation is 0.0491 and the mean is 1.009 for 14 data. For non-uniform heat flux, the standard deviation is 0.0609 and the mean is 0.980 for 23 data. The difference between the deviations from the means of the two sets of data is 1.18 %, with the uniform heat flux shape giving the 2.9 % higher in mean P/M ratio. So the non-uniform heat flux effect is properly treated in COBRA-TF with EPRI correlation.

As a result, COBRA-TF with EPRI correlation predicts well the CHF heat flux along with no turbulent mixing and no void drift effects. It is very interesting results. It maybe said that the two fluid model probably estimates the effects inherently, to some extent, in the transverse exchange models and interfacial models.

To compare the CHF predictability of two-fluid model with that of the homogeneous model, the COBRA-IV was used to analyze the data for test section 110. The results were included in Table 3. The statistics of P/M were 0.1281 for standard deviation and 1.019 for the mean. Comparing the results of both codes, COBRA-IV slightly overestimated the predictions and is twice in standard deviation relative to COBRA-TF. Therefore it turned out that COBRA-TF has the better performance in the prediction of DNB heat flux, within the examined range, than COBRA-IV.

III. Conclusions

COBRA-TF was assessed through dryout experiments in a tube and CHF tests in rod bundles. It is concluded from the analyses that

- There are good agreement of the dryout point and post-CHF temperature profile between the measurements and the predictions. Thus entrainment/deposition and post-CHF heat transfer models are validated at least within the range of the assessments.
- COBRA-TF code with EPRI correlation predicts well the CHF data for two kinds of rod bundles having axially uniform and non-uniform heat flux. The statistics of 37 data is as follows: the mean and standard deviation of P/M are 0.991 and 0.0577, respectively. From the comparisons of CHF predictability, COBRA-TF/EPRI showed better performance than COBRA-IV/EPRI
- Turbulent mixing model in COBRA-TF needs further investigation because the sensitivity study turned out that unexpectedly smaller mixing coefficient resulted in flatter distribution at the subchannel exit qualities. On the other hand a small effect of void drift factor was found relative to turbulent mixing parameter.

References

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Table 1. Comparison of Bennett's Dryout Location Data and COBRA-TF Predictions

Run No.	Mass Velocity (Mlb/ft2hr)	Heat Flux (Mbtu/ft2hr)	Subcooling (°F)	Dryout Location (inch)		
				Measurement	Prediction	Error
5359	0.29	1.727	78	140	154	+ 14
5294	1.44	3.477	42	164	173	+ 9

Table 2. Sensitivities of Turbulent Mixing and Void drift Parameters on DNBR

	Turbulent Mixing (β)	Void Drift(κ)	MDNBR
1.	0.0	0.0	0.976
2.	0.001	0.0	0.968
3.	0.001	10.0	0.972
4.	0.003	0.0	0.942
5.	0 003	10.0	0.961
6.	0.01	0.0	0.883

Table 3. summary of the statistical results of P/M for COBRA-TF/ EPRI and COBRA-IV/ EPRI

	no. of data	COBRA-TF/ EPRI		COBRA-IV/ EPRI	
		μ	σ	μ	σ
TS 102	14	1.009	0.0491		
TS 110	23	0.98	0.0609	1.019	0.1281
Total	37	0.99	0.0577		

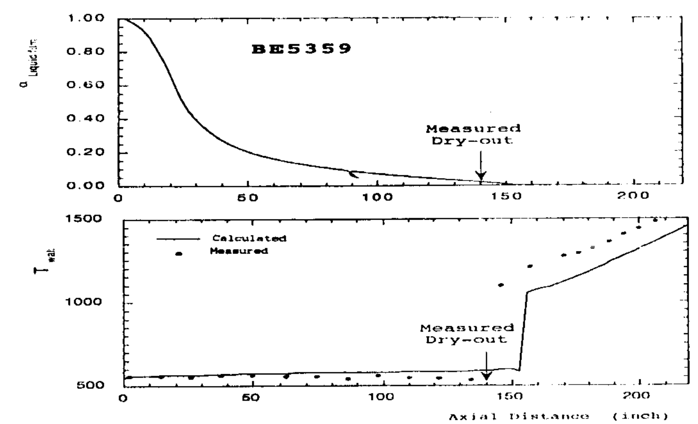


Figure 1. Comparison between the Measured and the Calculated for Dryout Locations and Wall Temperature Profile(BE5359)

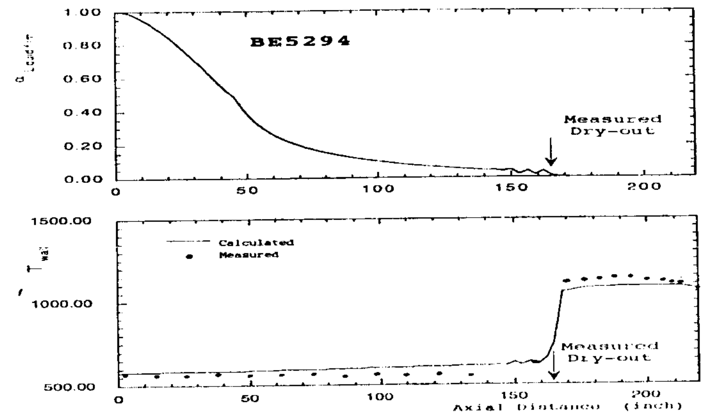


Figure 2. Comparison between the Measured and the Calculated for Dryout Locations and Wall Temperature Profile(BE5294)

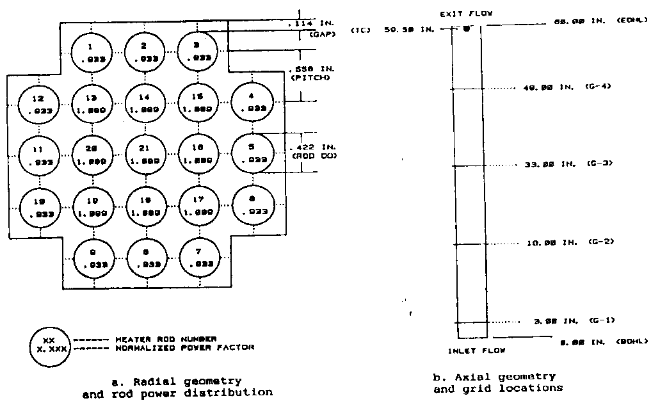


Figure 3. Radial and Axial Geometries for TS102

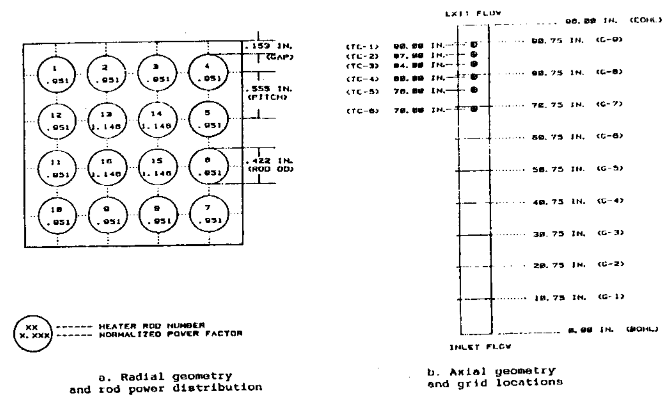


Figure 4. Radial and Axial Geometries for TS110

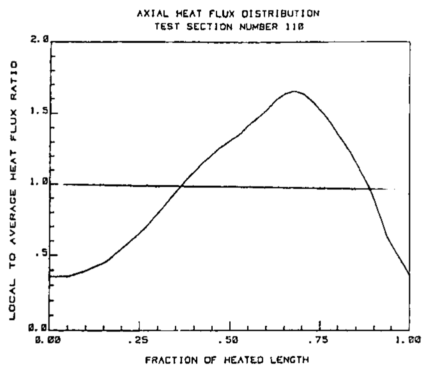


Figure 5. Axial Heat Flux Shape for TS102 and TS110

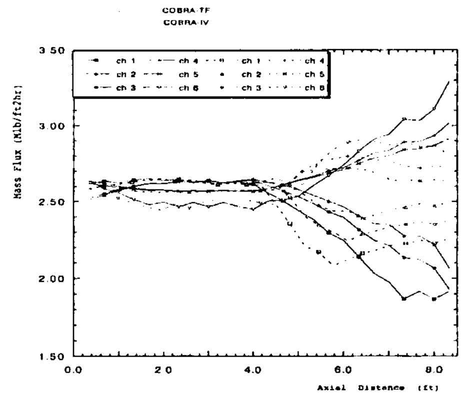


Figure 6. Comparison of Local Mass Flux Variations at the Subchannels between COBRA IV and COBRA-TF

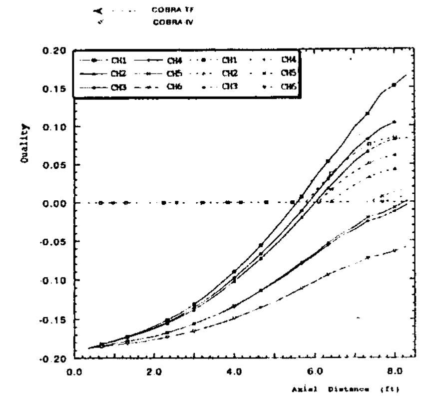
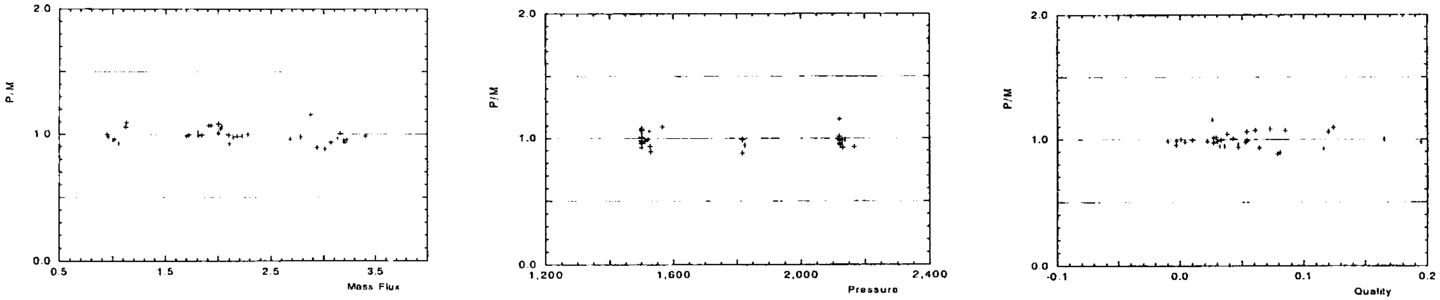


Figure 7. Comparison of Local Quality Variations at the Subchannels between COBRA IV and COBRA TF



(a) (b) (c)

Figure 8. P/M Residuals vs. Local Qualities