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Horizontal Stratified Flow Model for the 1-D Module of WCOBRA/TRAC-TF2: Modeling and Validation

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Abstract

For a two-phase flow in a horizontal pipe, the individual phases may separate by gravity. This horizontal stratification significantly impacts the interfacial drag, interfacial heat transfer and wall drag of the two phase flow. For a PWR small break LOCA, the horizontal stratification in cold legs is a highly important phenomenon during loop seal clearance, boiloff and recovery periods. The low interfacial drag in the stratified flow directly controls the time period for the loop clearance and the level of residual water in the loop seal. Horizontal stratification in hot legs also impacts the natural circulation stage of a small break LOCA. In addition, the offtake phenomenon and cold leg condensation phenomenon are also affected by the occurrence of horizontal stratification in the cold legs.

In the 1-D module of the WCOBRA/TRAC-TF2 computer code, a horizontal stratification criterion was developed by combining the Taitel-Dukler model and the Wallis-Dobson model, which approximates the viscous Kelvin-Helmholtz neutral stability boundary. The objective of this paper is to present the horizontal stratification model implemented in the code and its assessment against relevant data. The adequacy of the horizontal stratification transition criterion is confirmed by examining the code-predicted flow regime in a horizontal pipe with the measured data in the flow regime map. The void fractions (or liquid level) for the horizontal stratified flow in cold leg or hot leg are predicted with a reasonable accuracy.

Keywords

Horizontal Stratification, LOCA, WCOBRA/TRAC-TF2

1. Introduction

The simulation of a PWR small break LOCA (SBLOCA) transient is, to some extent, determined by the two-phase flow regime present in the horizontal pipes of the RCS. Therefore, in the FULL SPECTRUM™ LOCA (FSLOCA™) Phenomena Identification and Ranking Table (PIRT) [1], cold leg horizontal stratification was assigned as a high ranking phenomenon during the loop seal clearance, boiloff, and recovery periods for small breaks. For intermediate breaks, similar considerations apply to the accumulator and safety injection periods. Horizontal stratification in the hot leg was ranked as medium during the natural circulation stage of small breaks. Horizontal stratification was also ranked as high for loop seal clearance. However, the validation of loop seal clearance model will be provided in a separated publication, and this study focuses on horizontal stratification in cold leg or hot leg.

WCOBRA/TRAC-TF2 is a new generation Westinghouse safety evaluation code developed for FSLOCA™ methodology. WCOBRA/TRAC-TF2 combines 3-D module of WCOBRA/TRAC code and 1-D module of TRAC-PF1/MOD2 code [2]. Therefore, the two-fluid, six-equation formulation of the two-phase flow is utilized for the 1-D loop components in WCOBRA/TRAC-TF2. The new formulation is more appropriate to describe loop phenomena during a SBLOCA scenario, especially when a characterization of separated flow in the loop is required. However, the formulation of the horizontal flow regime in the original version of the TRAC-PF1/MOD2 code was rather simplistic. The flow regime criterion for the transition from non-stratified to horizontal stratified flow regime was based on critical vapor and liquid superficial velocities. The criterion was derived from the horizontal flow regime map developed by Mandhane et al. [3]. However, the transition criterion lacks dependency on pressure and hydraulic diameter, and it was found inconsistent with relevant data such as the JAERI Two-Phase-Test-Facility (TPTF) [4].

A modified version of the well recognized Taitel-Dukler [5] model was adopted in the early version of WCOBRA/TRAC-TF2 to predict horizontal stratification in 1-D module. Taitel and Dukler (T-D) model represents the first complete semi-theoretical horizontal flow regime transition theory. The modified Taitel-Dukler transition criterion was assessed against various test data at different pressures and pipe diameters. The prediction matched reasonably well with the test data. The scaling on the pressure and pipe size was well addressed by modified Taitel-Dukler model [2]. However, the modified Taitel-Dukler model tends to under-predict the critical velocity at a low void fraction as shown in Fig. 6 of reference [2].

The traditional horizontal flow regime transition models such as Taitel-Dukler and Wallis Dubson [6] were developed using inviscid Kelvin-Helmholtz (IKH) stability theory. Recently, horizontal stratification models developed by Crowley et. al. [7] and Barnea and Taitel [8] incorporated viscous effect of fluid into the Kelvin-Helmholtz interface instability study. The theoretical framework is referred to as viscous Kelvin-Helmholtz (VKH) in this discussion. Those models are more accurate than traditional interfacial stability models and are able to capture interfacial stability at extreme high or low void fractions, low liquid/gas density ratio, and large fluid viscosity. However, these models are too complicated to implement into the WCOBRA/TRAC-TF2 safety analysis code. The traditional inviscid Kelvin-Helmholtz models and together with uncertainty studies is judged to be adequate for the prediction of horizontal stratification in FSLOCA™ methodology. However, the neutral stability boundary of the advanced viscous Kelvin-Helmholtz model is utilized to improve the horizontal flow regime transition criteria in WCOBRA/TRAC-TF2.

For the horizontal stratification model developed for WCOBRA/TRAC-TF2, the transition criterion is affected by the prediction of void fraction, or water level, in a stratified pipe with the given liquid and gas superficial velocities. From horizontal stratified flow, the void fraction is determined by the interfacial drag, wall drag, and inlet/outlet boundary condition (via gravitational water head term) for a horizontal pipe. The importance of the interfacial drag model for a correct prediction of the stratified regime has been sometimes overstated in the literatures [4] [9]. In the high mass flux case, the wall drag to the liquid phase has more influence in determining the level in the pipe which results in some impact to the transition between stratified and non-stratified regimes. Thus, an accurate prediction of the interfacial drag in the stratified regime is seen of secondary importance for high mass flux flow. The interfacial drag has more influence on defining the void fraction (level) in the pipe for low to medium mass flux flow. Both the inlet boundary condition and outlet boundary condition are expected to play a role on the prediction of the void fraction for a stratified flow in a horizontal pipe. The influence of the boundary condition propagates along the pipe through the gravitational water head term in the momentum equation. If the flow is supercritical, usually for high mass flux flow, the downstream outlet boundary condition is not able to impact the flow in the pipe. The boundary condition shows more impact on the flow in short pipes, such as cold leg and hot leg in PWR, than the flow in a long pipe, since the equilibrium state of flow is unlikely to be reached for a short pipe.

The wall friction model for horizontal stratified flow in WCOBRA/TRAC-TF2 is Blasius model [10], which showed enough accuracy of the predicted wall friction for the Reynolds number range in a PWR LOCA. The gravitational water head term was implemented in the momentum equations in WCOBRA/TRAC-TF2. Therefore, the assessment of this study focuses on the interfacial drag model together with the influence of the inlet and outlet boundaries.

In this study, the previous horizontal stratification model in WCOBRA/TRAC-TF2 is further improved to obtain better agreement with experimental data and prediction from viscous Kelvin-Helmholtz neutral stability boundary. The prediction of void fraction in horizontal stratified flow is compared with relevant test data to assess the stratified flow interfacial drag model, wall drag model, and influence of inlet and outlet boundaries.

The improved horizontal stratification model for WCOBRA/TRAC-TF2 is described in Section 2. Section 3 focuses on the assessment on the void fraction prediction for horizontal stratified flow. The assessment is against ROSA TPTF experimental data, which is described in Section 3.1. The WCOBRA/TRAC-TF2 input model for TPTF facility and the calculation are briefly discussed in Section 3.2. The results of the assessment are presented in Section 3.3. Section 4 is the conclusions.

2. Improvement on the Horizontal Stratification Model

In WCOBRA/TRAC-TF2, the modified Taitel-Dukler horizontal stratification transition criterion [2] is represented in dimensionless form as shown in Eq. (1)

$$j^*_{gl,TD}(\alpha) = \left(1 - \frac{h_l}{D}\right)\sqrt{\frac{\alpha^3 \pi D}{4S_i}} \tag{1}$$

where j^*_{gl} is a modified Wallis number, h_l is the depth of the liquid layer, α is the void fraction, D is the pipe diameter, and S_i is the two-phase interfacial length in the cross section of pipe. A modified Wallis number j^*_{gl} is defined in Eq. (2) using the liquid velocity, the vapor velocity, the void fraction, the pipe diameter, gravitational acceleration, and fluid densities.

$$j_{gl}^* = \frac{|u_g - u_l|\alpha}{\sqrt{\frac{\rho_l - \rho_g}{\rho_g} Dg}} \tag{2}$$

The modified Taitel-Dukler model tends to under-predict the Wallis number at a low void fraction, which leads to lower predicted critical relative velocity between two phases (Figure 1). To correct the accuracy of prediction at low void fraction, a further adjustment on the transition criteria is made. In the Taitel-Dukler transition criterion, that the parameter ($1-h_l/D$) approaches zero as void fraction is near zero. It is speculated that when void fraction is very small the transition criterion should be independent of ($1-h_l/D$), especially for a large diameter pipe. This is the approach employed by Wallis-Dobson [6], although their model was targeted at a rectangular channel.

$$j_{gl,WD}^*(\alpha) = 0.5\sqrt{\frac{\alpha^3 \pi D}{4S_i}} \tag{3}$$

The calculation of transition criterion in the Wallis-Dobson model is similar to that of the modified Taitel-Dukler model with the constant 0.5 replacing ($1-h_l/D$).

Figure 1 compares the modified Wallis-Dobson model (relative velocity replacing gas phase velocity), the modified Taitel-Dukler model, and various experimental horizontal stratification data, which are summarized in Table 1. The experiments cover range of pressures up to 7.3MPa and include full scale geometry scaling of interest. It can be seen that the Wallis-Dobson model matches better with the trend of data at low void fractions, but under-predicts transition criteria at high void fractions. Figure 1 suggests that the Wallis-Dobson model is a better model for the transition at low void fractions at various pressure and pipe diameters.

In order to combine the merits of the Taitel-Dukler model and the Wallis-Dobson model, a hybrid horizontal stratification criterion was developed to fit the experimental data better. The model utilizes the modified Taitel-Dukler model at high void fractions and transitions into the modified Wallis-Dobson model at lower void fractions. The constants in both models are fine adjusted to better match experimental data. The boundary between the two models exists near α=0.5. The curve of predicted modified Wallis number j_{gl}* as function of void fraction is plotted in Figure 2 together with experimental transition data in Table 1. In Figure 2, the uncertainty multiplier of the hybrid model is determined as 0.5~1.5 by ranging the constant of the model to fit available flow regime transition data.

Table 1 Data Sources of Horizontal Stratification Experiments

Test	ID (m)	Pressure (MPa)	Fluid
TPTF [10]	0.18	3	Steam-water
TPTF [10]	0.18	5	Steam-water
TPTF [10]	0.18	7.3	Steam-water
Moon and No [12]	0.7	0.1	Steam-water
Smoglie [12]	0.205	0.5	Steam-water
Crowley et al. [7]	0.089	0.54	Gas-water
Crowley et al. [7]	0.17	0.54	Gas-water

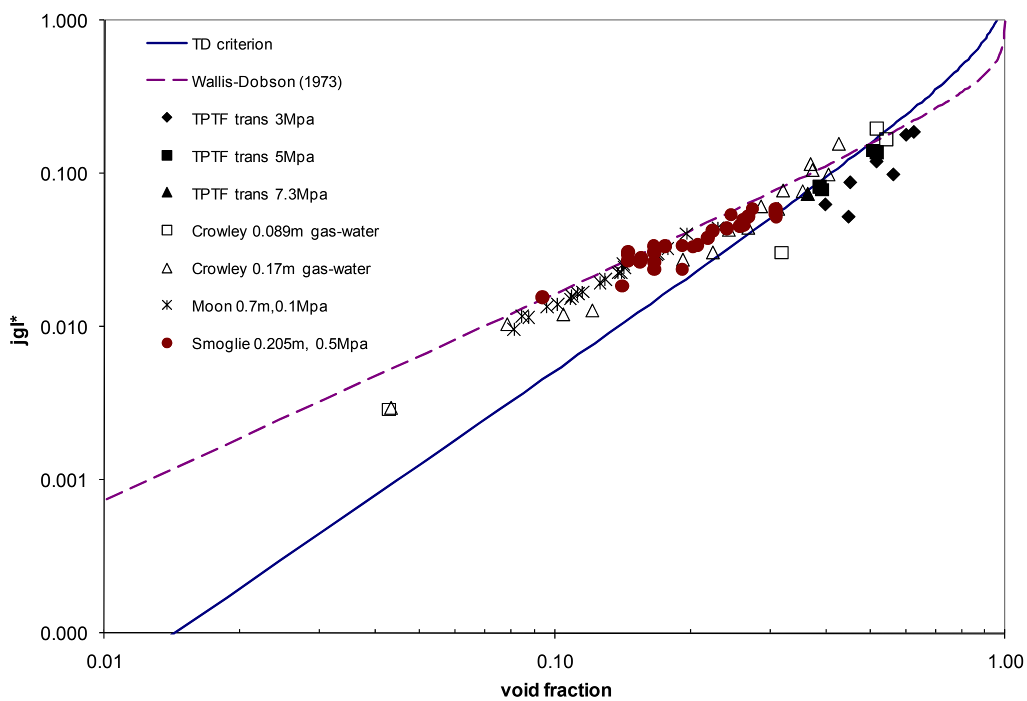

Figure 1 Comparison between Modified Taitel-Dukler Transition Model and Modified Wallis-Dobson Transition Model

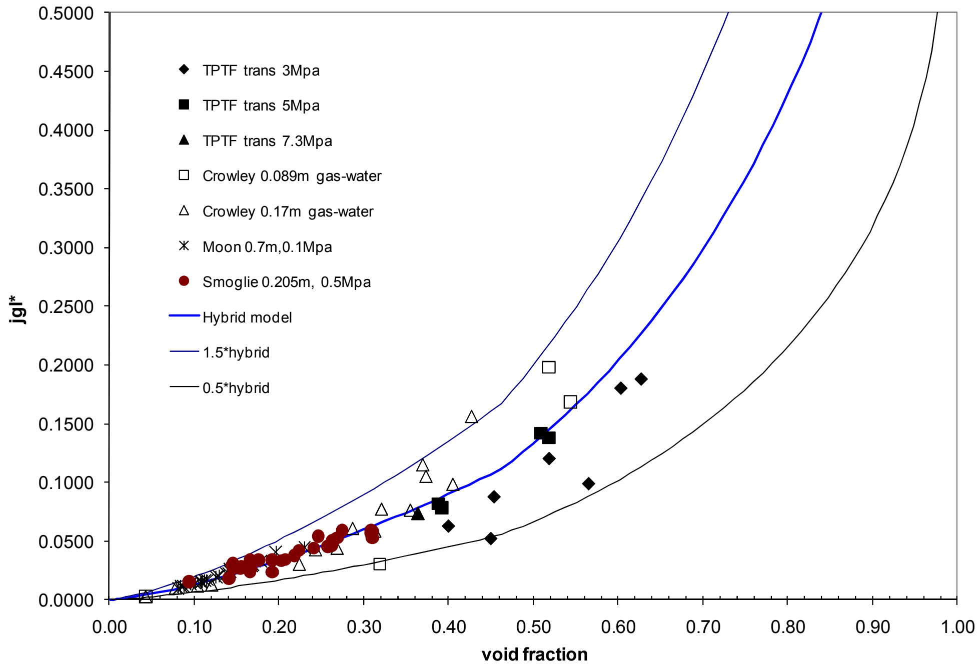

Figure 2 Horizontal Stratified Flow Regime Transition and Relevant Data

As discussed before, there are more sophisticated horizontal stratification models [7] [8] which include the viscous effects of fluid in the Kelvin-Helmholtz interface instability study. The VKH model is not incorporated into WCOBRA/TRAC-TF2 code because of the complexity. Instead, the Taitel-Dukler type transition criterion, i.e., the hybrid model is adopted for WCOBRA/TRAC-TF2.

However, the prediction of the VKH model was utilized to justify the scaling capability of the hybrid model. Three transition boundaries of steam water stratified flow at pressures of 3 MPa and 7 MPa and pipe diameters of 0.18 m and 0.7 m are compared against the hybrid transition model in Figure 3. Those three cases properly cover the range of PWR SBLOCA conditions. The curves of those 3 cases collapse together in the plot of j_{gl}* versus void fraction, even though both the pressures and pipe diameters vary significantly. This supports the choice of a simplified transition criterion (the hybrid model) based on the relationship of the void fraction and modified Wallis number. Figure 3 shows that the hybrid model matches the VKH model well for almost the entire void fraction range with the exception of void fractions at the extremes. The discrepancy between the hybrid model and the VKH model at extremely low void fraction is judged insignificant. The discrepancy at high void fraction is much smaller than the uncertainty range of 0.5~1.5 for the hybrid model. Thus, the discrepancy at high void fraction is judged insignificant for SBLOCA simulation.

Figure 4 shows the improved flow regime map for 1-D module of WCOBRA/TRAC-TF2 together with JAERI TPTF test data [13], which will be used for the assessment of void fraction prediction in Section 3. The basic regime map serves for non-stratified flow for both vertical and horizontal flow. The basic flow regime map consists of bubbly, bubbly slug, churn (or transition), and annular-mist flow regime. The bubbly flow regime occurs for $\alpha \leq 0.3$, the bubbly slug regime for 0.3 <α≤0.5, the churn regime for 0.5 <α≤0.75, and the annular-mist regime for α>0.75. In addition, bubbly slug flow could not occur if the total mass flux exceeded 2700 kg/m^2-s. The stratified flow is disabled if the mass flux is larger than 2700 kg/m^2-s.

The hybrid stratified flow transition criterion mixing Taitel-Dukler model and Wallis-Dobson model is the solid line in Figure 4. A small interpolation region between the stratified flow and non stratified flow exists to make a smooth transition.

A wavy dispersed flow regime is added to the horizontal pipe flow. The wavy-dispersed flow regime replaces part of churn and bubbly flow in the basic regime map. The wavy-dispersed flow regime is only applied to void fraction less than 0.75 because of similarity between the wavy-dispersed flow and annular-mist flow. The transition criteria and the entrainment model of wavy-dispersed flow were discussed in the previous publication [2].

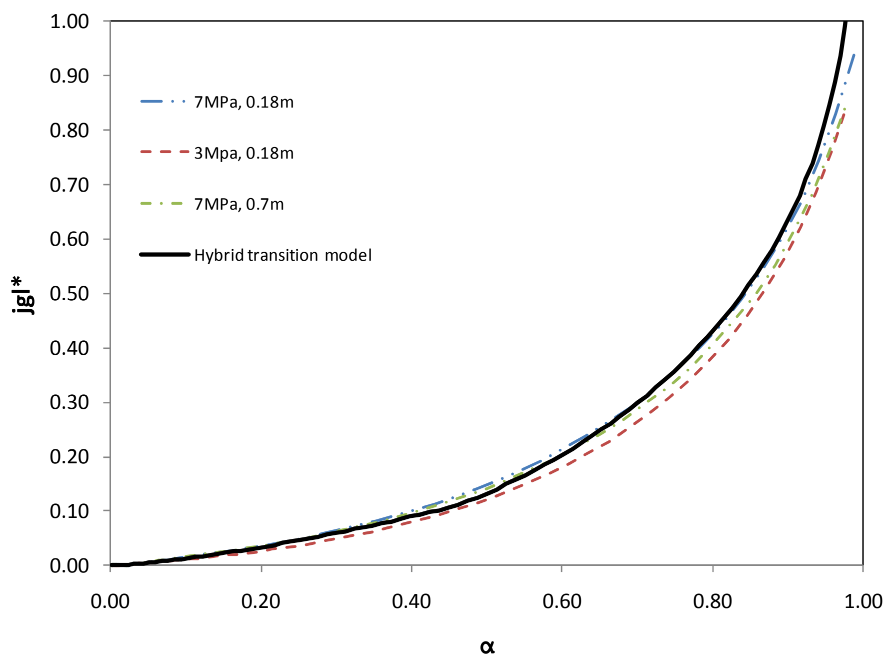

Figure 3 Comparison between Hybrid Horizontal Stratification Criterion and Viscous Kelvin Helmholtz Models at Various Pressures and Pipe Diameters

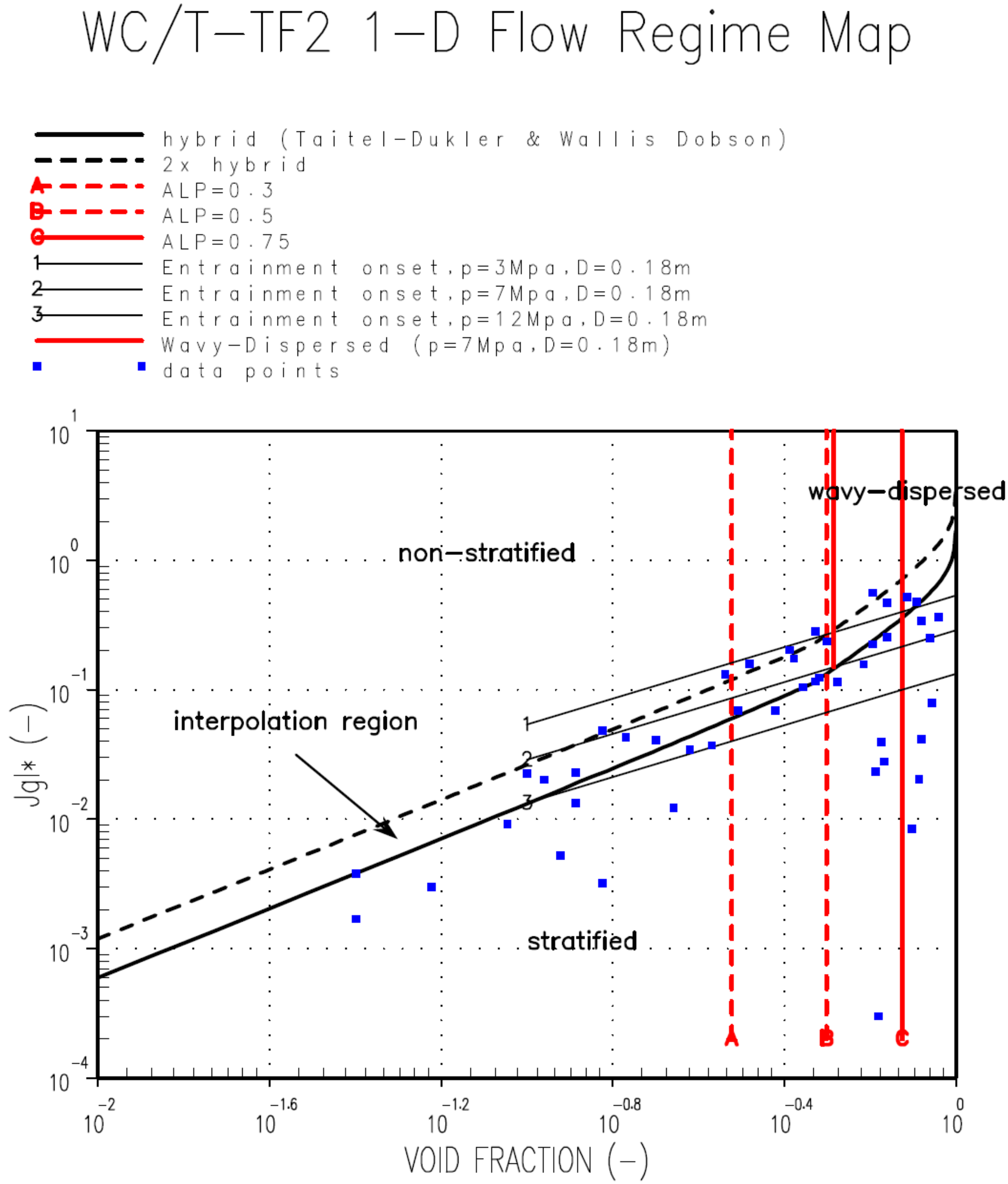

Figure 4 Horizontal Flow Regime Map Including Wavy-Dispersed Regime (α<0.75) together with TPTF Test Data. Both Void Fraction and Modified Wallis Number is Based on Logarithmic Scale. Entrainment Onset Criterion for Wavy-Dispersed Regime Was Discussed in Reference [2].

3. Assessment on Void Fraction Prediction

The adoption of a transition criterion as a function of the modified Wallis number and local void fraction allows the criterion to predict the flow transition for non-equilibrium state flow. In this section, the assessment focuses on the accuracy of void fraction prediction by WCOBRA/TRAC-TF2. The prediction of void fraction is controlled by the wall drag, the interfacial drag and the gravitational water head. The applicability of the wall drag model for stratified flow was justified. The gravitational water head term was implemented in the WCOBRA/TRAC-TF2 momentum equations. Therefore, the assessment focuses on the interfacial drag model together with the influence of the inlet and outlet boundaries.

The assessment is made against Two-Phase Flow Test Facility (TPTF) stratified flow data. TPTF [13] is a Japan Atomic Energy Research Institute (JAERI) steam-water stratified flow test with a large scale pipe diameter, high pressure, and broad range of flow rates and void fractions. These characteristics render TPTF tests to be excellent benchmark tests for the stratification in small break LOCA. The interfacial and wall drag models for the stratified flow in WCOBRA/TRAC-TF2 are assessed via comparison between the measured void fraction and the predicted void fraction.

3.1 TPTF Experiments

TPTF [13] was designed and built by JAERI to study the nature of SBLOCA. This facility was designed to perform various steam/water two-phase flow and heat transfer experiments at steady state and at pressures up to 12.8 MPa. These experiments were characterized by a high system pressure (3~12 MPa), a large test section diameter (0.18 m) and a wide range of mass flux (40 to 1000 kg/m^2-s) obtained in the test section for concurrent saturated two-phase flow. The test also simulated the pump effect at inlet, and the water level effect at outlet. These characteristics render TPTF to be an ideal test to assess SBLOCA safety evaluation codes.

Figure 5 shows the flow loop used in the TPTF, which consisted of an electrically heated boiler, separate pumps for steam and water lines, a mixer and a 10 m long, 180 mm inner diameter (ID) horizontal test section. The saturated water and slightly superheated steam merged inside the T-shaped mixer. There were two types of T-shaped mixers used in TPTF experiments as schematically shown in Figure 6. Early series of tests used "bubbly flow" type of mixer. The steam was introduced horizontally into a bundle of tubes and was forced out through numerous holes drilled along the side of each tube. Liquid introduced from the bottom of the tee flowed on the outside of the tube bundle, where the steam and liquid mixed with each other. A nearly homogeneous mixture of liquid and vapor was expected to enter the test section. This homogeneous mixture is similar to the two-phase flow condition in cold leg after a rotating reactor coolant pump (RCP). The data of Kawaji et al. [13] came from this "bubbly flow" type mixer. However, because of the homogeneous flow type inlet, the flow was far away from the equilibrium state horizontal stratified flow. The void fraction tended to be larger than the equilibrium state flow and the relative gas-liquid speed was lower than the relative speed in equilibrium state stratified flow. Thus, the non-equilibrium stratified flow due to the homogeneous flow inlet tended to be stable according to horizontal stratification model. The length of cold leg pipe (L/D=56) was not long enough to allow flow reach equilibrium state from the homogeneous mixture. Another problem associated with "bubbly flow" mixer is that the entrained bubbles cannot be released rapidly from liquid if the speed of liquid is large. Those factors led to the observation that the separated to slug flow transition never appeared in the tests with "bubbly-flow" mixer. The TPTF data points are plotted in the WCOBRA/TRAC-TF2 flow regime map in Figure 4. There is a substantial amount of data points beyond the horizontal stratification transition boundary of WCOBRA/TRAC-TF2. The discrepancy between the WCOBRA/TRAC-TF2 flow regime map and the observed stratified flow regime in the experiment is likely attributed to the entrained bubbles induced by the "bubbly flow" mixer at the inlet. Nevertheless, the data with the homogenous inlet mixer are still applicable to assess the interfacial drag and the prediction of void fraction.

The later TPTF tests used a "separated-flow" type mixer, which contained a horizontal flat plate. Due to this flat plate, the two phases entered the test section as a separated two-phase flow. The height of the separator plate was either 0.3 or 0.7 in height-to-diameter ratio. Thus, there was essentially no bubble entrainment and the flow was not far away from the equilibrium state horizontal stratified flow. All the TPTF flow regime transition data by JAERI were obtained with a "separated flow" type mixer (Anoda et al. [15]). The TPTF data from the "separated-flow" mixer was utilized to verify the stratification transition criteria for WCOBRA/TRAC-TF2. In this section, the data from the "bubbly-flow" mixer are applied to assess the interfacial drag and the prediction of void fraction.

The water level at the exit of the test section was controlled by the water level in the boiler. There were two water levels in the TPTF tests. In the case of high water level, the water level in the boiler was 0.4 m higher than the center of the test section pipe. In the case of low water level, the water level in the boiler was 0.4 m lower than the center of the test section pipe. The purpose of high or low water level was to simulate the effect of downcomer. The effect of full or empty downcomer was simulated in TPTF test.

The overall length of the test section was 10.0 m and the length-to-diameter ratio (L/D) was 56. The volumetric flow rates of vapor and liquid entering the test section were changed independently by adjusting the flow control valves and the pump speed. The maximum volumetric flow rates were 0.194 m^3/s for steam and 0.047 m^3/s for liquid. For the 180 mm ID test section, the maximum superficial liquid and vapor velocities were 1.9 and 7.6 m/s, respectively. The horizontal test section was equipped with various two-phase flow instruments. To measure density (or void) distribution, two of the γ-densitometers were located near the inlet (L/D=17) and outlet (L/D=48) of the test section.

A large matrix of tests was conducted by JAERI during 1980s. Part of the data is available in literature [13] . The TPTF data are selected as the primary data source for the assessment because of the following reasons:

1). Addressed full scale of pressure (3~12 MPa).

2). The pipe diameter (0.18 m) is the largest pipe diameter for high pressure steam-water stratified flow test.

3). TPTF is approximately the same size of the cold leg of the ROSA Integral Effects Test facility, which the major SBLOCA validation case for WCOBRA/TRAC-TF2.

4). The overall length of the pipe is 10.0 m and the length-to-diameter ratio (L/D) is 56, which reduces the influence of inlet and outlet boundary conditions. In the assessment, the boundary conditions are incorporated into the input model for the simulation to assess the influence of inlet and outlet boundary condition on the void fraction prediction.

5). Wide range of mass flux (40-1000 kg/m^2-s) and void fraction (0.06~0.97).

6). Outlet condition simulating empty/full downcomer effect in PWR.

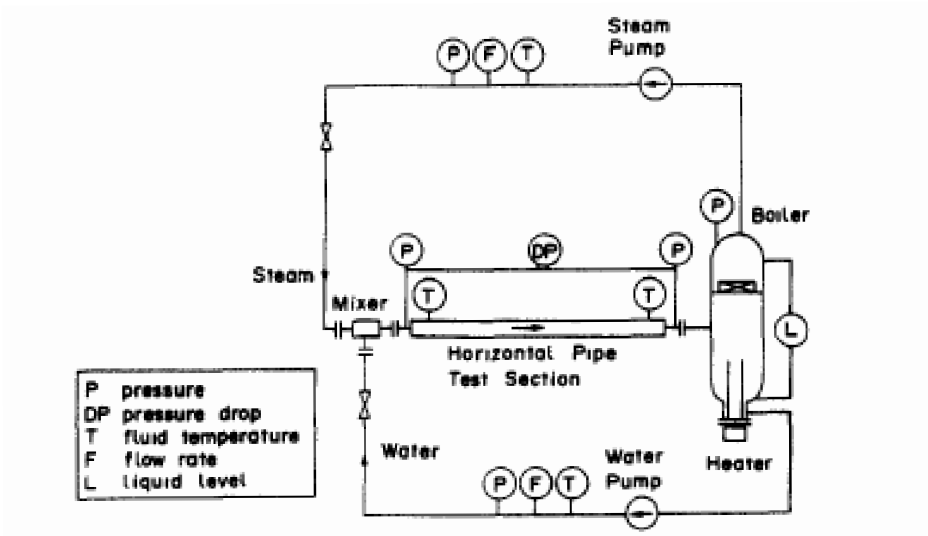

Figure 5 The Schematic Plot of the TPTF Facility [13]

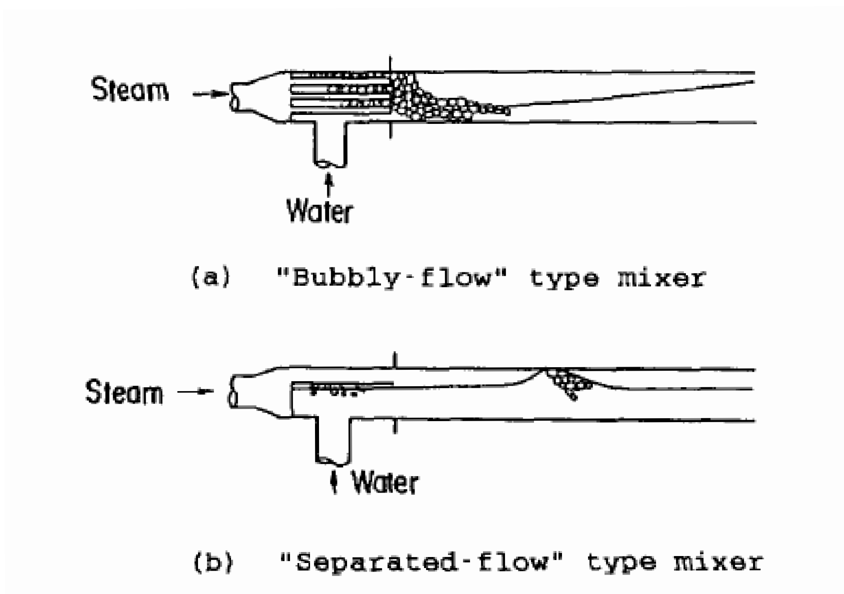

Figure 6 T-Shaped Mixers used in TPTF [15]

3.2 WCOBRA/TRAC-TF2 Input Model

The WCOBRA/TRAC-TF2 model includes the TPTF pipe from the location of first void fraction measurement point (L/D=17) to the exit to the water tank. The pipe from the homogeneous mixer to the first void fraction measurement point at L/D=17 is neglected. The inlet of the pipe is modeled with flow boundary conditions (FILL component) by providing the specific j_g and j_l for each test run. The measured void fraction at L/D=17 determines the gas phase velocity and the liquid phase velocity for the FILL component. The water level in the tank is simulated by setting the void fraction in the outlet pressure boundary condition.

The noding diagram is shown in Figure 7. The cold leg in the TPTF test section is intended to represent the PWR's cold leg. However, the L/D of the TPTF pipe is longer than the L/D of the PWR's cold leg, but not long enough to develop an equilibrium state stratified flow. The boundary conditions of the TPTF tests have been incorporated into the input model. Thus, the non-equilibrium state stratified flow, as well as the influence from the boundary condition, is part of the simulation.

The total number of computational nodes is 16 and the actual DX of computational node is 0.434 m. The second void fraction measurement point (L/D=48) in the TPTF test is located at node 13 in the WCOBRA/TRAC-TF2 model. The diameter of the TPTF pipe is similar to that of the ROSA IV/LSTF test facility, which is the SBLOCA Integral Effects Test for WCOBRA/TRAC-TF2 validation. Thus, the noding size for TPTF test is consistent with the cold leg model for ROSA IET to preserve the geometric similarity.

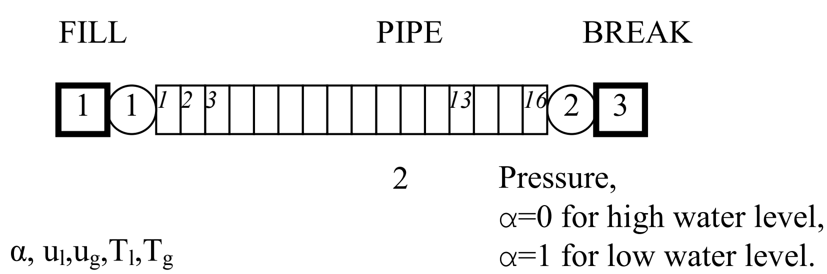

Figure 7 WCOBRA/TRAC-TF2 Input Models for TPTF. The Fill Component Corresponds to the Location of L/D=17 in the TPTF Facility.

3.3 Results

The simulation is carried out until a steady-state condition is reached. A typical void fraction profile in the pipe is shown in Figure 8 together with the flow regime numbers for TPTF test 722. Per Table 2 in reference [13], Run 722 was a low mass flux case with a high water level in the boiler. The Wallis number and the void fraction indicate the flow in TPTF test 722 is horizontal stratified (but near the transition boundary) per the WCOBRA/TRAC-TF2 flow regime map.

The code-predicted flow regime number of each node is marked with "N". It is seen that the flow regime numbers are either 2 or 4 in the nodes of the PIPE component, except the last node in the pipe. These flow regime numbers of 2, 4, or 6, which represent horizontal stratified flow at respective void fraction $\alpha \le 0.5$, $0.5 < \alpha \le 0.75$ or $0.75 < \alpha$, indicate horizontal stratified flow is developed in the pipe except for the exit. The flow enters the interpolation region at the exit (flow regime number less than 2) because the void fraction in the BREAK component is assumed to be zero.

The WCOBRA/TRAC-TF2 predicted void profile is shown with the solid line in Figure 8. The squares represent the measured void fractions at L/D=17 and L/D=48. The agreement between the measured void fraction and the predicted void fraction at L/D=48 is good. The dashed line (TD void fraction) represents the theoretical void fraction that would be obtained assuming the steady-state equilibrium in an infinitely long pipe as shown in Taitel and Dukler [5]. Obviously in this case, the pipe is of finite length and the boundary conditions have a strong impact on the solution. Thus, the measured and predicted void fraction is far away from the equilibrium state void fraction.

Figure 9 presents the void fraction distribution and the flow regime numbers for TPTF test 845, which was a high mass flux case with a low water level in the boiler. The flow is in the interpolation region according to the WCOBRA/TRAC-TF2 flow regime map. The void fraction in the pipe gradually increases, and the void fraction at node 13 (L/D=48) is slightly over-predicted. At the node 1 of the pipe (L/D=18), which is node 2 in Figure 10, the flow regime is less than 6, which indicates the interpolation region. Inside the pipe, as the void fraction increases, the flow regime numbers gradually approach 6 (horizontal stratified flow).

The stability of horizontal stratified flow in TPTF tests are evaluated using the hybrid transition criteria developed for WCOBRA/TRAC-TF2 with the measured void fraction at L/D=17 and L/D=48. The stability of horizontal stratified flow predicted using measured void fraction at L/D=17 and L/D=48, together with the predicted flow regime by WCOBRA/TRAC-TF2 at node 1 (L/D=18) and node 13 (L/D=48) are collected in Table 2. It is noted that the FILL component is a boundary node, so the flow regime is not evaluated by the code. Instead, the node 1 (L/D=18) of the PIPE is utilized to evaluate the flow regime near the entrance.

The prediction by the hybrid transition criteria in Table 2 confirm that near half of the TPTF data points are unstable if a horizontal stratified flow is assumed, as shown in Figure 4. In Table 2, for the points being predicted as an unstable horizontal stratified flow, the WCOBRA/TRAC-TF2 predicted flow regime is either in the interpolation region or the wavy-dispersed flow regime. In only few runs (755, 1545, 1547, and 1549), contrary to expectations, the flow regime predicted by WCOBRA/TRAC-TF2 is horizontal stratified. This is attributed to a slightly higher predicted void fraction. Overall, Table 2 demonstrates that the code is able to predict the transition from the horizontal stratified flow regime to non-horizontal stratified flow regime as intended.

Figure 10 compares the predicted void fraction at node 13 (L/D=48) with the measured void fraction at L/D=48 for the runs predicted as horizontal stratified at node 13. The predicted void fractions are within ±10% error bar with only one point notably beyond the upper error bar.

4. Conclusions

An improved horizontal flow regime map is included in the 1-D module of WCOBRA/TRAC-TF2 to expand the applicability of the code to small break LOCA scenarios. The 1-D module is based on the TRAC-PF1 formulation. TRAC-PF1 shortcomings are identified and corrected with a revised model which better describes the conditions expected in a PWR during postulated LOCA scenarios.

The improved model includes a hybrid transition criterion for the transition from horizontal stratified flow to non-horizontal stratified flow, taking the merits of both the Taitel-Dukler criterion and the Wallis-Dobson criterion. A wavy-dispersed model, sharing similarity with the annular-mist flow, is added to replace the bubbly slug/churn flow regime at low void fraction for a horizontal flow. Comparison between predicted flow regime and estimated flow regime using flow regime map demonstrates that the WCOBRA/TRAC-TF2 code is able to predict the transition from the horizontal stratified flow regime to non-horizontal stratified flow regime for flows in cold leg or hot leg as intended.

The void fraction prediction for the horizontal stratified flow is assessed against relevant test data. Results are in good agreement with the experiments. The void fractions are predicted within an accuracy of 10% except only one point. The horizontal stratification transition criterion is confirmed by examining the code-predicted flow regime number with the measured data in the flow regime map. The bias/uncertainty of void fraction prediction for the horizontal stratified flow in cold leg or hot leg is very small and is absorbed by the uncertainty treatment of the horizontal stratification transition model.

Table 2 Comparison Between Prediction from Horizontal Stratification Criteria and Prediction from WCOBRA/TRAC-TF2

Run	Stability of Horizontal Stratified Flow per Flow Regime Map using Measured Void Fraction (Yes/No)		WCOBRA/TRAC-TF2 Predicted Flow Regime	
	L/D=17	L/D=48	Node 1 (L/D=18)	Node 13 (L/D=48)
857	No	No	Wavy-Dispersed	Wavy-Dispersed
855	No	No	Wavy-Dispersed	Wavy-Dispersed
853	No	No	Interpolation Region	Interpolation Region
851	No	No	Interpolation Region	Interpolation Region
849	No	No	Horizontal Stratified	Horizontal Stratified
845	No	No	Interpolation Region	Interpolation Region
843	No	No	Wavy-Dispersed	Wavy-Dispersed
847	Yes	Yes	Horizontal Stratified	Horizontal Stratified
836	Yes	Yes	Horizontal Stratified	Horizontal Stratified
838	Yes	Yes	Horizontal Stratified	Horizontal Stratified
1561	Yes	Yes	Horizontal Stratified	Horizontal Stratified
1563	Yes	Yes	Horizontal Stratified	Horizontal Stratified
1565	Yes	Yes	Horizontal Stratified	Horizontal Stratified
1567	Yes	Yes	Horizontal Stratified	Horizontal Stratified
834	Yes	Yes	Horizontal Stratified	Horizontal Stratified
1555	Yes	Yes	Horizontal Stratified	Horizontal Stratified
1557	Yes	Yes	Horizontal Stratified	Horizontal Stratified
1559	Yes	Yes	Horizontal Stratified	Horizontal Stratified
779	Yes	Yes	Horizontal Stratified	Horizontal Stratified
781	Yes	Yes	Horizontal Stratified	Horizontal Stratified
775	Yes	Yes	Horizontal Stratified	Horizontal Stratified
751	No	No	Interpolation Region	Interpolation Region
749	No	No	Interpolation Region	Interpolation Region
747	No	No	Interpolation Region	Interpolation Region
773	Yes	No	Horizontal Stratified	Wavy-Dispersed
743	No	No	Wavy-Dispersed	Wavy-Dispersed
732	Yes	No	Horizontal Stratified	Interpolation Region
730	Yes	Yes	Horizontal Stratified	Horizontal Stratified
783	No	No	Interpolation Region	Interpolation Region
785	Yes	Yes	Horizontal Stratified	Horizontal Stratified
755	No	No	Horizontal Stratified	Horizontal Stratified
757	Yes	Yes	Horizontal Stratified	Horizontal Stratified
759	Yes	Yes	Horizontal Stratified	Horizontal Stratified
761	Yes	Yes	Horizontal Stratified	Horizontal Stratified
726	Yes	Yes	Horizontal Stratified	Horizontal Stratified
728	Yes	Yes	Horizontal Stratified	Horizontal Stratified
708	Yes	Yes	Horizontal Stratified	Horizontal Stratified
710	Yes	Yes	Horizontal Stratified	Horizontal Stratified
1545	No	No	Horizontal Stratified	Horizontal Stratified
1547	No	No	Horizontal Stratified	Horizontal Stratified
1549	No	No	Horizontal Stratified	Horizontal Stratified
763	Yes	No	Horizontal Stratified	Horizontal Stratified
720	Yes	No	Horizontal Stratified	Horizontal Stratified
722	Yes	No	Horizontal Stratified	Horizontal Stratified
712	Yes	Yes	Horizontal Stratified	Horizontal Stratified
714	Yes	Yes	Horizontal Stratified	Horizontal Stratified

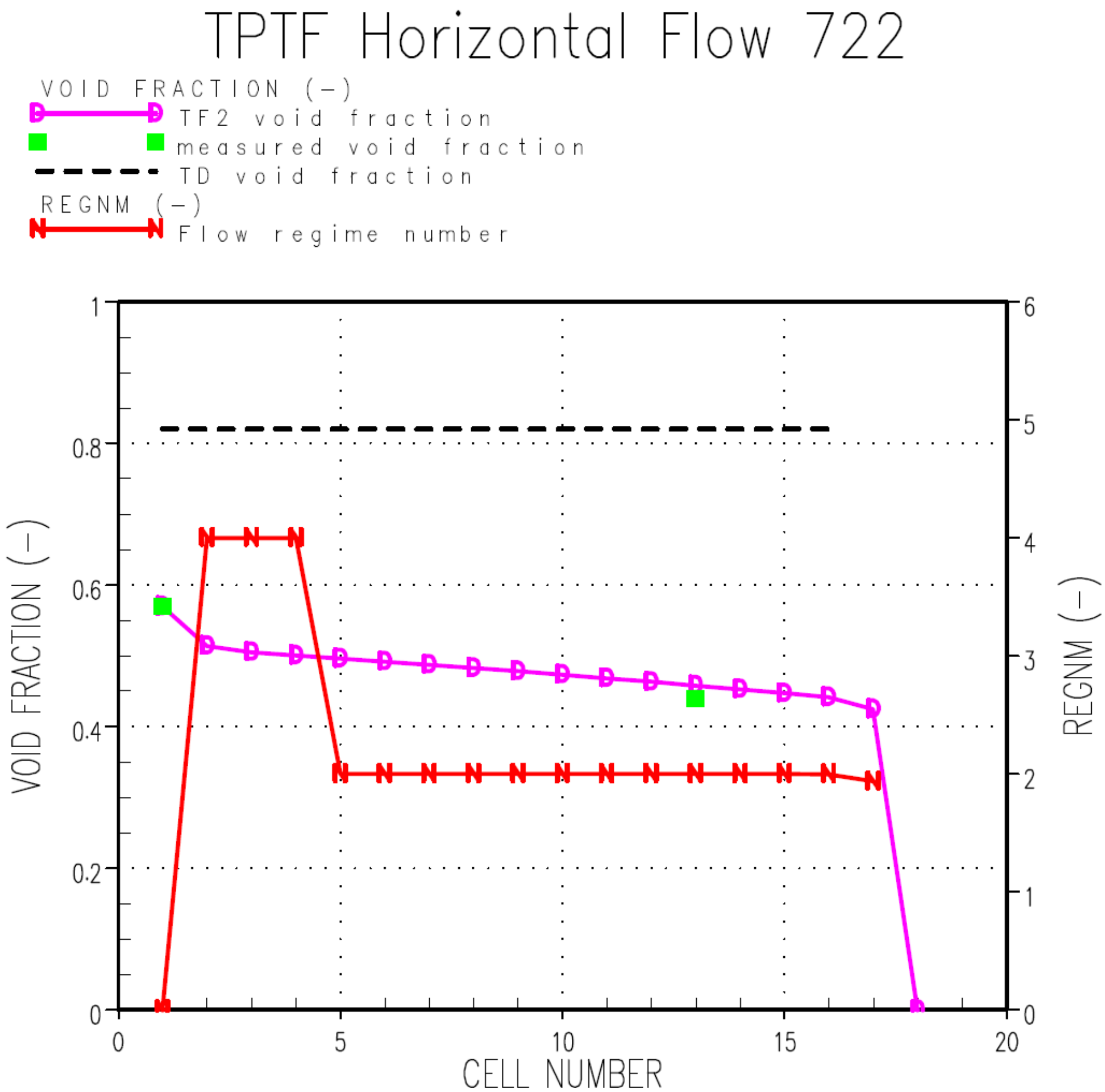

Figure 8 Comparison Between Measured Void Fraction in TPTF Run 722 and Predicted Void Fraction; TD Void Fraction is Equilibrium State Void Fraction using Taitel Dukler Formulas [5].

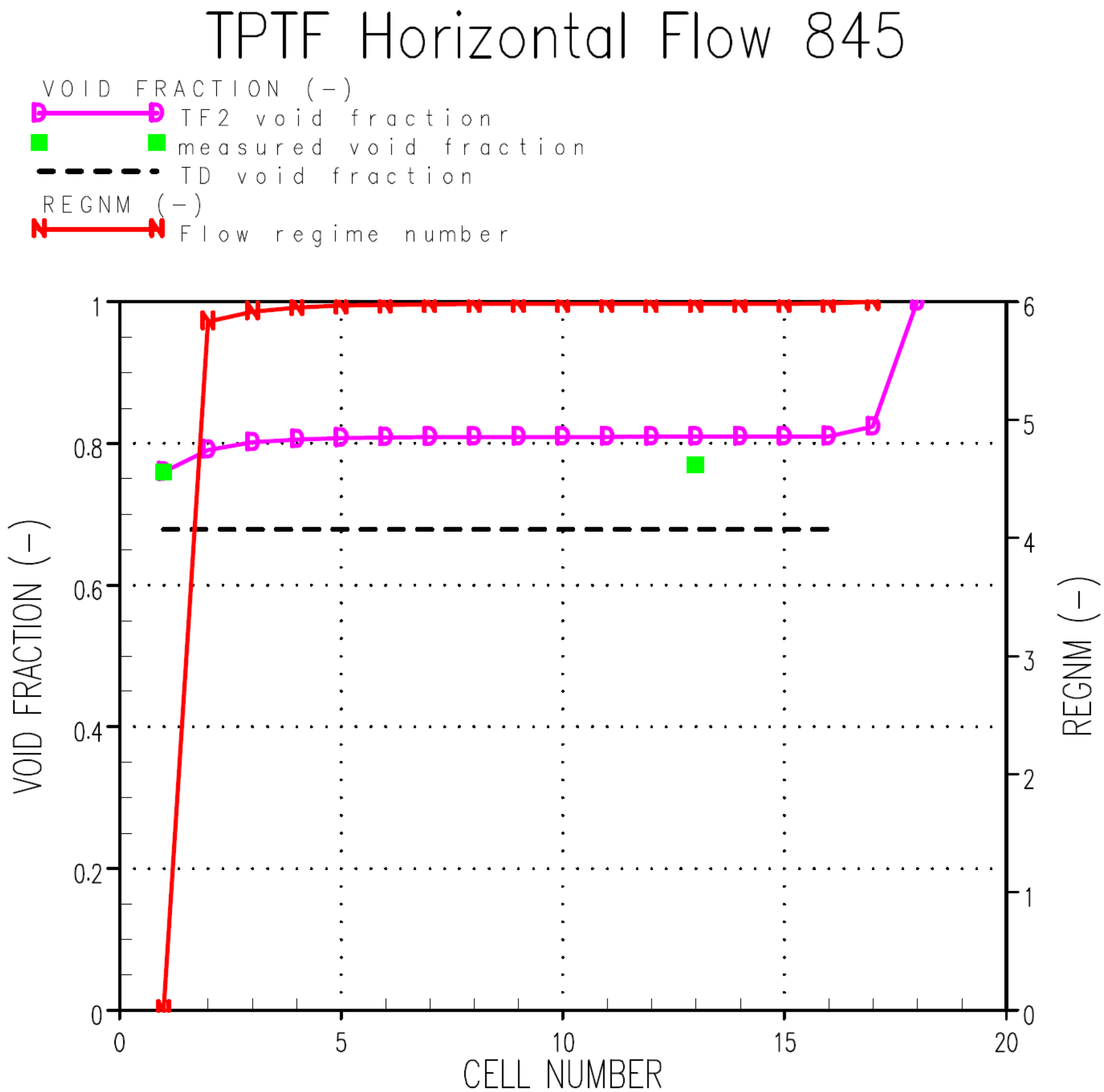

Figure 9 Comparison Between Measured Void Fraction in TPTF Run 845 and Predicted Void Fraction

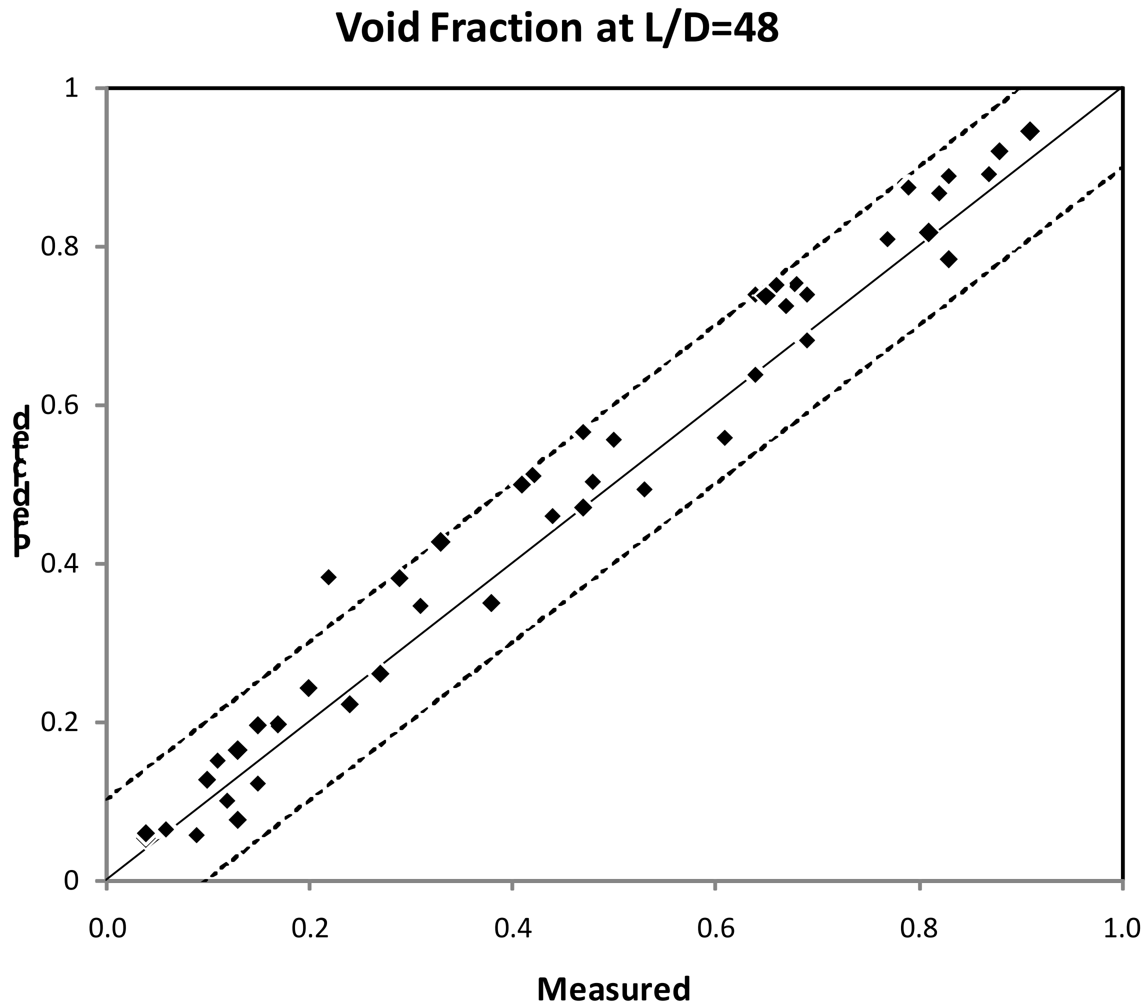

Figure 10 Comparison Between the TPTF Measured Void Fraction and the Predicted Void Fraction at L/D=48; Dash Lines Represent ±10% Accuracy.

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