JAERI-M
85-219

ASSESSMENT OF TRAC-PF1/MOD1 FOR COUNTERCURRENT-ANNULAR AND STRATIFIED FLOWS

January 1986

Akira OHNUKI

日 本 原 子 力 研 究 所
Japan Atomic Energy Research Institute

JAERI-Mレポートは，日本原子力研究所が不定期に公刊している研究報告書です。
入手の問合わせは，日本原子力研究所技術情報部情報資料課（〒319－11茨城県那珂郡東海村）あて，お申しこしください。なお，このほかに財団法人原子力弘済会資料センター（〒319-11茨城県那珂郡東海村日本原子力研究所内）で複写による実費頒布をおこなっております。

JAERI-M reports are issued irregularly.
Inquiries about availability of the reports should be addressed to Information Division, Department of Technical Information, Japan Atomic Energy Research Institute, Tokai-mura, Naka-gun, Ibaraki-ken 319-11, Japan.

編集兼発行　日本原子力研究所
印　　刷　日立高速印刷株式会社

Assessment of TRAC-PF1/MOD1 for Countercurrent - Annular and Stratified Flows

Akira OHNUKI
Department of Nuclear Safety Research,
Tokai Research Establishment, JAERI

(Received December 23, 1985)

I performed an independent assessment of the Transient Reactor Analysis Code, TRAC-PF1/MOD1, using air-water countercurrent-flow limitation data in circular pipes for annular, annular-mist, and stratified flows. Tubes were configurated in the vertical direction with different lengths and diameters and at angles of 60°, 40°, 20°, and 0° from the horizontal, respectively. Also, comparisons were made with data from a horizontal tube with an inclined riser at the end that simulated a pressurized water reactor (PWR) hot leg. TRAC-PF1/MOD1 was modified to study the effects of using two different correlations for interfacial shear in the annular-mist flow regime: the Wallis and Bharathan correlations. TRAC-PF1/MOD1 with the Wallis correlation predicts the point of no water penetration (bypass point) in the annular-mist flow regime except for the 40° inclined tube. However, for the region of partial water penetration, use of the Bharathan correlation in TRAC-PF1/MOD1 gives better agreement with data. Additional form losses were required at both ends of the tube to predict the flow rate of falling water accurately for the vertical tube. In the stratified-flow regime, TRAC-PF1/MOD1 underpredicts the air velocity which gives the bypass point but gives good agreement for the region of partial penetration. For the case of a simulated PWR hot leg, the code yields similar results to those obtained for the stratified-flow regime.

Keywords: PWR-LOCA, Two-Phase Flow, Countercurrent Flow, CCFL, Interfacial Shear, Independent Assessment, TRAC Code, Reflux Mode

---

This work was funded by the US Nuclear Regulatory Commission, Office of Nuclear Regulatory Research, Division of Accident Evaluation.

対向環状流および対向層状流に対するＴＲＡＣ－ＰＦ１／ＭＯＤ１の予測性能の評価

日本原子力研究所東海研究所原子炉安全工学部
大貫　晃

（1985年12月23日受理）

環状流，環状噴霧流および層状流の流動様式を示す円管内での空気－水の対向流制限（ＣＣＦＬ）のデータを使い，加圧水型炉の冷却材喪失事故を対象とするＴＲＡＣコード（ＰＦ１／ＭＯＤ１バージョン）の予測性能の評価を行った。円管形状としては，長さおよび内径をパラメータとする垂直管，水平からの角度60°，40°および20°の傾斜管および水平管を用いた。また加圧水型炉のホットレグを模擬した傾斜管付き水平管のデータに対しても評価を行った。環状流の相関摩擦係数に対しては，Wallis型およびBharathan型の２種類の相関式を使えるようにし，その効果を調べた。

データとの比較から，Wallis型の相関式は40°の傾斜管の場合を除き，落水が止まる点（バイパス点）をよく予測した。一方落水を生じる領域ではBharathan型のほうがよりよい予測を示すものの，正確に予測するためには円管の上下端に付加的な形状摩擦損失係数を与えねばならないことがわかった。層状流のデータに対しては，バイパス点を与える空気流速をＴＲＡＣコードは過小評価するものの落水を生じる領域に対してはよい予測を与えた。ホットレグ模擬管に対しては層状流に対する予測結果と同様の傾向を示した。

本研究は，米国原子力規制委員会（ＵＳＮＲＣ）の予算で行った成果である。

CONTENTS

目　　次

List of TABLE

List of FIGURES

I. INTRODUCTION

One important phenomenon of two-phase flow during a postulated pressurized water reactor (PWR) loss-of-coolant accident (LOCA) is the limit for falling water with countercurrent flow. Suppression of the flow rate for falling water with upward steam flow at the end-box tie plate, located at the interface between the upper plenum and core, and in the downcomer is important because falling water contributes directly to core cooling. Countercurrent-flow limitation (CCFL) at these locations is characterized by CCFL in the vertical configurations. Suppression of water backflow in the hot legs against the upper-plenum steam flow is important because of its effect on steam binding in the primary loops. Steam binding governs core-inlet coolant velocity during a reflood phase in a large-break LOCA and affects water accumulation in the upper plenum and resultant fallback core cooling during reflux cooling in a small-break LOCA. CCFL in the hot legs is characterized by CCFL in the inclined riser tube and attached horizontal tube. Therefore, CCFL in configurations with an inclination angle from vertical to horizontal is one of the important phenomena during a LOCA in a PWR.

Flow regime for CCFL in a vertical tube has been reported as annular flow.[(1),(2)] The CCFL flow regime in the inclined channel and horizontal tube has been reported as stratified or stratified-slug flow.[(3),(4)] Therefore, the capability of the Transient Reactor Analysis Code (TRAC)[(5),(6)] to predict results that compare well with CCFL data for countercurrent--annular and stratified flows is a significant part of predicting hydraulic behavior during a LOCA in a PWR.

The objective of this study is to assess the capability of TRAC-PF1/MOD1 to predict results that compare well with CCFL data for vertical tubes with different lengths and diameters; for tubes with an inclination angle of 60°, 40°, 20°, or 0° from the horizontal, respectively; and for a simulated PWR hot leg. It has been reported that the flow rate of falling water mainly depends on interfacial drag between liquid and gas phases for vertical CCFL.[(1),(7)] The TRAC-PF1/MOD1 code adopts the Wallis-type interfacial-shear correlation[(8)] for annular and annular-mist flows. The Wallis correlation was derived from cocurrent annular-flow data in tubes with diameters ranging from 0.0254 to 0.0762 m. As an alternative, a correlation proposed by Bharathan[(1)] for annular flow also is examined in this report. The Bharathan correlation, which includes the hydraulic-diameter effect, was derived from countercurrent air-water annular-flow data in tubes up to 0.152-m diameter.

It has been reported that the use of this correlation in TRAC-PF1/MOD1 provides good agreement for both perforated-plate and downcomer geometry.[9]

II. TRAC-PF1/MOD1 INTERFACIAL SHEAR MODELS

This section discusses annular and annular-mist interfacial-shear, stratified-flow wall-shear, and interfacial-shear models used in this study.

An annular or annular-mist flow regime is assumed in TRAC-PF1/MOD1 for a void fraction greater than 0.75 and above a tube inclination angle of 30° from the horizontal. TRAC-PF1/MOD1 solves the mass, momentum, and energy equations for both liquid and gas phases. In the annular-mist regime, total interfacial shear is calculated by summing drag caused by gas flow around droplets and drag on the liquid film. Because only one liquid field equation is solved, the momentum exchange between droplets and liquid film is not accounted for. Liquid fraction that exists as mist is obtained from an entrainment correlation, which combines a simple S-shaped entrainment correlation based on the critical Weber number and a correlation by Kataoka and Ishii.[10] Thus,

$$E = \max \{1 - \exp [0.5(V_E - V_g)V_E] \ ,$$

$$7.75 \times 10^{-7} \times We_e(Re_\ell We_e)^{1/4}\} \ ,$$

where

E = fraction of liquid entrained as droplets,

$$V_E = 1.32\left[\frac{(\rho_\ell - \rho_g)\sigma g We}{\rho_g^2}\right]^{1/4} \ ,$$

$$We = \frac{\rho_\ell (V_g - V_e)^2 D_d}{\sigma} \ ,$$

$$We_e = \frac{\rho_g j_g^2 D_h}{\sigma}\left(\frac{\rho_\ell - \rho_g}{\rho_g}\right)^{1/3} \ , \quad \text{and}$$

$$Re_\ell = \frac{\rho_\ell j_\ell D_h}{\mu_\ell} \ .$$

It has been reported that the use of this correlation in TRAC-PF1/MOD1 provides good agreement for both perforated-plate and downcomer geometry.[9]

II. TRAC-PF1/MOD1 INTERFACIAL SHEAR MODELS

This section discusses annular and annular-mist interfacial-shear, stratified-flow wall-shear, and interfacial-shear models used in this study.

An annular or annular-mist flow regime is assumed in TRAC-PF1/MOD1 for a void fraction greater than 0.75 and above a tube inclination angle of 30° from the horizontal. TRAC-PF1/MOD1 solves the mass, momentum, and energy equations for both liquid and gas phases. In the annular-mist regime, total interfacial shear is calculated by summing drag caused by gas flow around droplets and drag on the liquid film. Because only one liquid field equation is solved, the momentum exchange between droplets and liquid film is not accounted for. Liquid fraction that exists as mist is obtained from an entrainment correlation, which combines a simple S-shaped entrainment correlation based on the critical Weber number and a correlation by Kataoka and Ishii.[10] Thus,

$$E = \max \{1 - \exp\,[0.5(V_E - V_g)V_E]\ ,$$

$$7.75 \times 10^{-7} \times We_e(Re_\ell We_e)^{1/4}\}\ ,$$

where

E = fraction of liquid entrained as droplets,

$$V_E = 1.32[\frac{(\rho_\ell - \rho_g)\sigma g We}{\rho_g^2}]^{1/4}\quad ,$$

$$We = \frac{\rho_\ell(V_g - V_e)^2 D_d}{\sigma}\quad ,$$

$$We_e = \frac{\rho_g j_g^2 D_h}{\sigma}\,(\frac{\rho_\ell - \rho_g}{\rho_g})^{1/3}\quad , \quad \text{and}$$

$$Re_\ell = \frac{\rho_\ell j_\ell D_h}{\mu_\ell}\quad .$$

Volume mean-droplet diameter size, D_d, is determined by using a critical Weber number of 4.0. Drag caused by gas flow around entrained droplets is calculated by the following equation.

$$C_i = \frac{3C_b \alpha \rho_\ell}{4D_d} \quad ,$$

where $C_b = 0.44$.

Drag caused by liquid film is calculated in each computational cell by the following equation, based on a correlation by Wallis[8] that has been derived from cocurrent-annular-flow data for air and water in tubes with diameters ranging from 0.0254 to 0.0762 m,

$$C_i = 0.005[1.0 + 75.0(1 - \alpha)(1 - E)] \ .$$

To obtain the total interfacial-drag coefficient, droplet drag is weighted by the liquid fraction that is entrained, and Wallis' annular-flow drag is weighted by the fraction remaining as film.

In this study, an alternative annular interfacial-shear correlation proposed by Bharathan[1] also is examined. This correlation is given by the following equation.

$$C_i = 0.005 + A(\delta^*)^B \quad ,$$

where

$$\mathrm{Log}_{10}\, A = -0.56 + \frac{9.07}{D^*} \quad ,$$

$$B = 1.63 + \frac{4.74}{D^*} \quad ,$$

$$\delta^* = \frac{\delta}{\left[\frac{\sigma}{g(\rho_\ell - \rho_g)}\right]^{1/2}} \quad ,$$

$$D^* = \frac{D_h}{\left[\frac{\sigma}{g(\rho_\ell - \rho_g)}\right]^{1/2}} \quad .$$

This correlation was developed from an investigation of countercurrent--annular flow of air and water in tubes with diameters ranging from 0.0064 to 0.152 m. As shown in Ref. 9, for increasing liquid fraction and tube diameters, the Bharathan correlation gives a larger interfacial drag than Wallis.

A stratified-flow regime for a tube inclination angle of less than 30° from the horizontal is possible in TRAC-PF1/MOD1. Stratified flow is assumed if vapor velocity is less than twice a critical gas velocity that is found using the stratification criterion developed by Y. Taitel and A.E. Dukler,(11)

$$V_c = C2\left[\frac{(\rho_\ell - \rho_g) g \cos\theta \, A_g}{\rho_g \dfrac{dA_\ell}{dh_\ell}}\right]^{1/2} ,$$

where

$$C2 = 1 - \frac{h_\ell}{D_h} \quad \text{and}$$

$$\frac{dA_\ell}{dh_\ell} = \{D_h^{\,2} - (2h_\ell - D_h)^2\}^{1/2} .$$

Below the V_c value, the wall-shear coefficients are calculated by the Blasius relation that is based on a minimum turbulent Reynolds number. The interfacial-shear coefficient is assumed to be a constant (0.01) times the gas density. Above twice the V_c value, the standard flow-regime map is assumed. A cubic spline employing the independent variable V_g is used to connect the two end points.

III. TRAC INPUT MODEL

A. Model of Vertical Tube

Descriptions of CCFL test facilities for vertical tubes are documented fully in Refs. 1 and 2. The TRAC-PF1/MOD1 input model for these facilities is shown in Fig. 1. The test section is modeled using a PIPE component available in TRAC-PF1/MOD1, and the upper and lower plena are modeled by TEE components. Major dimensions of these components are summarized in Table I. Boundary conditions are specified using a FILL component for

This correlation was developed from an investigation of countercurrent-- annular flow of air and water in tubes with diameters ranging from 0.0064 to 0.152 m. As shown in Ref. 9, for increasing liquid fraction and tube diameters, the Bharathan correlation gives a larger interfacial drag than Wallis.

A stratified-flow regime for a tube inclination angle of less than 30° from the horizontal is possible in TRAC-PF1/MOD1. Stratified flow is assumed if vapor velocity is less than twice a critical gas velocity that is found using the stratification criterion developed by Y. Taitel and A.E. Dukler,[11]

$$V_c = C2\left[\frac{(\rho_\ell - \rho_g) g \cos\theta \, Ag}{\rho_g \frac{dA_\ell}{dh_\ell}}\right]^{1/2} ,$$

where

$$C2 = 1 - \frac{h_\ell}{D_h} \quad \text{and}$$

$$\frac{dA_\ell}{dh_\ell} = \{D_h^{\,2} - (2h_\ell - D_h)^2\}^{1/2} .$$

Below the V_c value, the wall-shear coefficients are calculated by the Blasius relation that is based on a minimum turbulent Reynolds number. The interfacial-shear coefficient is assumed to be a constant (0.01) times the gas density. Above twice the V_c value, the standard flow-regime map is assumed. A cubic spline employing the independent variable V_g is used to connect the two end points.

III. TRAC INPUT MODEL

A. Model of Vertical Tube

Descriptions of CCFL test facilities for vertical tubes are documented fully in Refs. 1 and 2. The TRAC-PF1/MOD1 input model for these facilities is shown in Fig. 1. The test section is modeled using a PIPE component available in TRAC-PF1/MOD1, and the upper and lower plena are modeled by TEE components. Major dimensions of these components are summarized in Table I. Boundary conditions are specified using a FILL component for injection of air into the lower plenum and a second FILL component for injection of water into the upper plenum. Two BREAK components are used to model the pressure boundary at the top of the upper plenum and overflow of the two-phase mixture at the side wall of the upper plenum, respectively. A FILL component is used to close the bottom of the lower plenum with zero velocity. An additive form-loss factor of 1.0 is added at both ends of the test tube, and 0.005 for the wall friction loss is added at each node inside the test tube.

The following procedure procedure was used to run the calculation. First, steady-state air flow was established using air injection; then, water was injected into the upper-plenum bottom cell. All components were adiabatic, and all runs were made using the air-water option in TRAC-PF1/MOD1. Air velocity in the test section was determined from the input FILL velocity. Flow rate for water falling through the test tube was determined graphically from a plot of the void-fraction slope in the lower-plenum bottom cell vs time.

Sensitivity calculations were performed to determine the effects of the liquid level in the overflow line attached to the upper plenum and of water injection flow into the bottom of the upper plenum. Any change in liquid level in the overflow line had very little effect on the overall results. However, any change in the water injection flow rate affected the flow rate of falling water for the large-diameter 0.152-m tube. Therefore, for the large-diameter tube, the maximum variation for downward liquid flow was obtained by varying the water injection flow rate for each air velocity used.

B. Models of Inclined Tube, Horizontal Tube, and Simulated PWR Hot Leg

Reference 12 describes the test facility used to study CCFL in inclined tubes and a simulated PWR hot leg. The horizontal-tube test facility is documented in Ref. 4. The TRAC-PF1/MOD1 input model for these facilities is shown in Fig. 2. The test section is modeled by a PIPE component, and the upper and lower plena are modeled by VESSEL components. Major dimensions of these components are summarized in Table I. Boundary conditions for the two FILL and two BREAK components are the same as those for the vertical-tube input model. All lines for air injection, water injection, overflow of the two-phase mixture, and air exhaust to the atmosphere are modeled as PIPE components. An additive K factor of 1.0 is entered for both ends of the test section. At each node inside the test section, a 0.005 loss coefficient is entered to model wall friction. The procedure for running the calculation and the method for calculating the flow rate of air and water in the test tube were the same as those for the vertical tube. Sensitivity calculations also were performed to assess the effect of changing the level of the overflow line attached to the upper plenum and the water injection flow. These changes had a negligible effect on the overall results.

IV. CALCULATED RESULTS AND COMPARISON WITH EXPERIMENTAL DATA

A. Annular-Flow Regime

Figure 3(a), (b), and (c) compares the data with TRAC-PF1/MOD1 predictions for the vertical tube. The data and predictions are plotted on $J_g^{*1/2}$ and $J_\ell^{*1/2}$ axes. The variable J_g^* represents dimensionless upward gas velocity, and J_ℓ^* is the dimensionless velocity of liquid delivered to the lower plenum. These velocities, J_g^* and J_ℓ^*, are defined as follows,

$$J_k^* = \frac{j_k \rho_k^{1/2}}{[gD_h(\rho_\ell - \rho_g)]^{1/2}} ,$$

where k = g or ℓ.

These parameters are based on the Wallis empirical correlation[8] that has been proposed as one of the typical correlations for CCFL in a vertical tube, that is,

$$J_g^{*1/2} + m\, J_\ell^{*1/2} = C,$$

where m and C are constants.

These parameters are used as the axes in the comparison plots throughout this document. Figure 3(a) compares the results for the short 0.05-m tube with a 0.025-m diameter; Fig. 3(b), for the long 1.52-m tube with a 0.0254-m diameter; and Fig. 3(c), for the large 0.152-m diameter tube with a 3.66-m length. Therefore, the comparisons in Fig. 3(a), (b), and (c) show the capability of TRAC-PF1/MOD1 to predict the scaling effect for the length and diameter of vertical tubes.

In Fig. 3(a), the TRAC-PF1/MOD1 prediction that is labeled "standard" shows good agreement with the data at the point of no water penetration (bypass point). The "standard" calculational results were obtained with the TRAC-PF1/MOD1 version that uses the Wallis correlation for annular-flow interfacial shear. TRAC overpredicts the flow rate of falling water in the

the flow rate of air and water in the test tube were the same as those for the vertical tube. Sensitivity calculations also were performed to assess the effect of changing the level of the overflow line attached to the upper plenum and the water injection flow. These changes had a negligible effect on the overall results.

IV. CALCULATED RESULTS AND COMPARISON WITH EXPERIMENTAL DATA

A. Annular-Flow Regime

Figure 3(a), (b), and (c) compares the data with TRAC-PF1/MOD1 predictions for the vertical tube. The data and predictions are plotted on $J_g^{*1/2}$ and $J_\ell^{*1/2}$ axes. The variable J_g^* represents dimensionless upward gas velocity, and J_ℓ^* is the dimensionless velocity of liquid delivered to the lower plenum. These velocities, J_g^* and J_ℓ^*, are defined as follows,

$$J_k^* = \frac{j_k \rho_k^{1/2}}{[g D_h (\rho_\ell - \rho_g)]^{1/2}} \quad ,$$

where k = g or ℓ.

These parameters are based on the Wallis empirical correlation[8] that has been proposed as one of the typical correlations for CCFL in a vertical tube, that is,

$$J_g^{*1/2} + m\, J_\ell^{*1/2} = C,$$

where m and C are constants.

These parameters are used as the axes in the comparison plots throughout this document. Figure 3(a) compares the results for the short 0.05-m tube with a 0.025-m diameter; Fig. 3(b), for the long 1.52-m tube with a 0.0254-m diameter; and Fig. 3(c), for the large 0.152-m diameter tube with a 3.66-m length. Therefore, the comparisons in Fig. 3(a), (b), and (c) show the capability of TRAC-PF1/MOD1 to predict the scaling effect for the length and diameter of vertical tubes.

In Fig. 3(a), the TRAC-PF1/MOD1 prediction that is labeled "standard" shows good agreement with the data at the point of no water penetration (bypass point). The "standard" calculational results were obtained with the TRAC-PF1/MOD1 version that uses the Wallis correlation for annular-flow interfacial shear. TRAC overpredicts the flow rate of falling water in the region of water penetration, that is, the region of $J_\ell^{*1/2}$ greater than 0.0. These tendencies also exist in the comparisons shown in Fig. 3(b) and (c). Note that the prediction for the large-diameter tube in Fig. 3(c) shows a variation of J_ℓ^* at a constant J_g^* caused by the amount of water injected into the upper plenum.

The entrainment model greatly influences the prediction of the bypass point, as shown in Fig. 3(a) in the curve labeled with a triangle. This prediction without entrainment shows much more water penetration for values of $J_g^{*1/2}$ greater than 0.7. The calculated flow regime in TRAC-PF1/MOD1 for this region of interest is annular and annular mist because the average void fraction in the tube was varied from 0.95 at $J_g^{*1/2}$ = 1.0 to 0.75 at $J_g^{*1/2}$ = 0.4. Therefore, the interfacial-shear model for the annular-mist flow regime can predict the bypass point of vertical tubes regardless of the diameter within the 0.0254-0.152-m range and regardless of the length within the 0.05-3.66-m range.

To minimize the difference between the "standard" code prediction and data in the region of water penetration, the Wallis annular interfacial-shear correlation was changed to the Bharathan correlation. Results using the Bharathan correlation are shown in Fig. 3(a), (b), and (c) as the square marks. Results in Fig. 3(a) do not show any improvement for the region of water penetration and underpredict the bypass point. Results in Fig. 3(b) and (c) show improvement for the region of water penetration and give good agreement for the bypass point. However, discrepancies still exist in the region of water penetration.

As shown in Fig. 3(b) and (c), the data are changed by the shape of the upper inlet of the test section, that is, more water penetration for the rounded inlet than for the square inlet. It has been suggested that the geometry at both ends of the vertical tube is important to predict the flow rate of falling water.(1) Therefore, a TRAC calculation with additional K factors at both ends of the test section was performed in an attempt to improve the predicted flow rate of falling water. These results also are included in Fig. 3(a), (b), and (c). These comparisons show that a K factor of 10.0 is required for the short tube and that a K factor of 100.0 is required for the calculation using the Bharathan correlation for the long tubes with large diameters. Because void fractions for the "standard" prediction and for the prediction with a K factor of 100.0 at $J_g^{*1/2}$ = 0.4 in Fig. 3(b) are 0.86 and approximately 0.75 in the bottom cell of the test tube, respectively, the better agreement attained with the increased

K factor is caused by the larger interfacial drag as liquid accumulates in the bottom of the tube, causing a flow-regime transition.

Figure 4 compares the data, the "standard" prediction, and the prediction using the Bharathan correlation for tubes with inclination angles of 60° and 40° from the horizontal. The capability of TRAC-PF1/MOD1 to predict the effects of these tubes is important because the angle of an inclined riser tube in a PWR hot leg is 50° from the horizontal. The calculated flow regime is annular and annular-mist flow similar to that in the vertical tubes because the normal flow-regime map is applied to tubes with an inclination angle greater than 30° from the horizontal; the range of the average void fractions in the tubes was greater than 0.75. As shown in Fig. 4, the "standard" prediction gives good agreement for the bypass point for a tube with 60° inclination but overpredicts water penetration at lower gas flows. The prediction for the same tube using the Bharathan correlation gives better overall agreement with the data. For the tube of 40°, the "standard" calculation underpredicts the bypass point but gives good agreement in the region of water penetration. The prediction for the tube of 40° using the Bharathan correlation gives similar results. Because it was unnecessary to add K factors at the ends of the test section for the inclined tubes to obtain good agreement with the data, flow limitation probably occurs in the test section rather than at the ends, as in the case of the vertical test section.

B. Stratified-Flow Regime

Figures 5 compares the data and code predictions for a horizontal tube and a tubd at an inclination of 20° from the horizontal. The calculated flow regime was stratified because the inclination angle of the tube is less than 30°, and the average air velocity in the tube ranges from 5.5 m/s at $J_g^{*1/2} = 0.6$ to 2.0 m/s at $J_g^{*1/2} = 0.3$. The "standard" code prediction for both tubes gives good agreement for the flow rate of falling water in the range of $J_g^{*1/2}$ less than 0.4, although data for the horizontal tube do not exist for the range of $J_g^{*1/2}$ greater than 0.25. The "standard" prediction for the tube of 20° inclination underpredicts the bypass point and the flow rate of falling water in the range of $J_g^{*1/2}$ greater than 0.4. These characteristics for the tube of 20° were not changed by modifying the K factor at both ends of the tube and eliminating entrainment, as shown in Fig. 5. Figure 6 compares the data, the "standard" code prediction, and the prediction with some modifications for the simulated PWR hot leg. The "standard" code prediction is in fair agreement with the data for the range of $J_g^{*1/2}$ less than 0.3 but underpredicts complete bypass at approximately $J_g^{*1/2} = 0.35$. Removing the entrainment model or adding extra form losses at both ends of the tube does not improve the predicted bypass point. These same tendencies are observed in the stratified-flow case shown in Fig. 5. The calculated flow regime in the horizontal section of the tube is stratified because average air velocity in that region is less than the critical velocity at the bypass point.

V. DISCUSSION OF RESULTS AND RECOMMENDATIONS

In comparing the TRAC-PF1/MOD1 calculated results with the experimental CCFL data, the following trends are observed.

1. The experimental flooding curves are sensitive to the diameter, length, inclination angle, and inlet geometry of the test section.
2. The standard code results show overall good agreement in the prediction of the point of complete bypass for vertical pipes, but allow too much water to fall back for lower air flows. In the case of pipes with low inclination angles, the code tends to underpredict the complete bypass point.
3. Changing the interfacial-shear correlation and varying the inlet loss coefficients can improve the comparison in some cases.

The sensitivity of the flooding data to the test-section geometry is not restricted to pipes of circular cross section. For example, tie-plate and downcomer geometries exhibit their own countercurrent flooding characteristics.(9) These comparisons show that it is very difficult to predict the complete flooding curve for a wide range of geometries or configurations with a single interfacial-shear correlation such as used in TRAC-PF1/MOD1. Therefore, to improve the code predictions for countercurrent flow of water and vapor, I recommend that the capability to input the flooding curve constants based on experimental data for specific geometries be added to TRAC-PF1/MOD1. Based on the input flooding curve constants, the code would be forced to a certain solution for the liquid velocity during CCFL situations. This would improve the code prediction for CCFL at specific locations selected by the user.

range of $J_g^{*1/2}$ less than 0.3 but underpredicts complete bypass at approximately $J_g^{*1/2} = 0.35$. Removing the entrainment model or adding extra form losses at both ends of the tube does not improve the predicted bypass point. These same tendencies are observed in the stratified-flow case shown in Fig. 5. The calculated flow regime in the horizontal section of the tube is stratified because average air velocity in that region is less than the critical velocity at the bypass point.

V. DISCUSSION OF RESULTS AND RECOMMENDATIONS

In comparing the TRAC-PF1/MOD1 calculated results with the experimental CCFL data, the following trends are observed.

1. The experimental flooding curves are sensitive to the diameter, length, inclination angle, and inlet geometry of the test section.
2. The standard code results show overall good agreement in the prediction of the point of complete bypass for vertical pipes, but allow too much water to fall back for lower air flows. In the case of pipes with low inclination angles, the code tends to underpredict the complete bypass point.
3. Changing the interfacial-shear correlation and varying the inlet loss coefficients can improve the comparison in some cases.

The sensitivity of the flooding data to the test-section geometry is not restricted to pipes of circular cross section. For example, tie-plate and downcomer geometries exhibit their own countercurrent flooding characteristics.[9] These comparisons show that it is very difficult to predict the complete flooding curve for a wide range of geometries or configurations with a single interfacial-shear correlation such as used in TRAC-PF1/MOD1. Therefore, to improve the code predictions for countercurrent flow of water and vapor, I recommend that the capability to input the flooding curve constants based on experimental data for specific geometries be added to TRAC-PF1/MOD1. Based on the input flooding curve constants, the code would be forced to a certain solution for the liquid velocity during CCFL situations. This would improve the code prediction for CCFL at specific locations selected by the user.

VI. CONCLUSIONS

We performed an independent assessment of TRAC-PF1/MOD1 using air-water CCFL data for annular, annular-mist, and statified flows. The configurations of test tubes examined in this assessment were vertical tubes with different scales for length and diameter; tubes with inclination angles of 60°, 40°, 20°, and 0° from the horizontal, respectively; and an inclined riser tube with a horizontal tube simulating a PWR hot leg. The following conclusions were obtained from this assessment.

1. TRAC-PF1/MOD1 using an annular-mist flow regime gave good agreement for the bypass point in a vertical tube and in a tube with an inclination angle of 60° regardless of the dimensions of the vertical tube, but underpredicted the bypass point for the tube inclined 40°.
2. TRAC-PF1/MOD1 using annular and annular-mist flow regimes overpredicted the flow rate of falling water for the vertical tube and the tube inclined 60°, but gave good agreement for the tube inclined 40°. Addition of K factors as form losses at both ends of the vertical tube is required to predict the flow rate of falling water accurately.
3. Use of the Bharathan correlation for the annular interfacial-shear model gives better agreement than the standard Wallis correlation used in TRAC-PF1/MOD1 for the region of partial water penetration, although additional form losses at the ends of the vertical tube are still required.
4. TRAC-PF1/MOD1 using the stratified-flow regime underpredicted the bypass point of the tubes with inclination angles of 20° and 0°, but gave good agreement for the flow rate of falling water for the region of partial water penetration.
5. The prediction for the simulated PWR hot leg showed good agreement for the flow rate of falling water for the region of partial water penetration. This agreement verifies the hot-leg CCFL that occurs during reflux cooling.
6. To enhance TRAC predictions of CCFL conditions, we recommend that the user should be able to specify flooding correlation constants in the input for specific locations. At these locations, the code would be forced to provide a certain liquid velocity during CCFL situations consistent with the input flooding correlation constants.

ACKNOWLEDGMENTS

This work was performed during the stay at Los Alamos National Laboratory (LANL) where the author was delegated as a resident engineer in 2D/3D program since February 1984 to March 1985.

The author is deeply grateful to M.W. Cappiello and F.E. Motley of LANL, Safety Code Development, Group Q-9, and K. A. Williams of Science Applications, Inc., Albuquerque, New Mexico, for their helpful advice and support. We also are grateful to the members of Reactor Safety Laboratory II, especially Y. Murao and H. Adachi, of the Japan Atomic Energy Research Institute. The author thanks F. M. Ortiz and A. E. Torres for typing the manuscript.

REFERENCES

1. D. Bharathan, "Air-Water Countercurrent Annular Flow," Electric Power Research Institute topical report NP-1165 (September 1979).
2. Y. Sudo and A. Ohnuki, "Mechanism of Falling Water Limitation under Counter-Current Flow through a Vertical Flow Path," Bulletin of the JSME, Vol. 27, No. 226 (April 1984).
3. S. C. Lee and S. G. Bankoff, "Stability of Steam-Water Countercurrent Flow in an Inclined Channel: Flooding," J. of Heat Transfer, Vol. 105, No. 4 (November 1983).
4. G. C. Gardner, "Flooded Countercurrent Two-Phase Flow in Horizontal Tubes and Channels," Int. J. Multiphase Flow, Vol. 9, No. 4 (1983).
5. D. Liles, et al., "TRAC-PF1/MOD1; An advanced best-estimate computer program for pressurized water reactor thermal-hydraulic analysis," Los Alamos National Laboratory," (February 1984) (draft copy).
6. D. Liles, et al., "TRAC-PD2; An advanced best-estimate computer program for pressurized water reactor loss-of-coolant accident analysis," Los Alamos National Laboratory report LA-8709-MS, NUREG/CR-2054 (April 1981).
7. A. G. Ostrogorsky, R. R. Gay, and R. T. Lahey, Jr., "The Prediction of Pressure Drop and CCFL Breakdown in Countercurrent Two-Phase Flow," J. of Heat Transfer, Vol. 105, No. 4 (November 1983).
8. G. B. Wallis, "One-Dimensional Two-Phase Flow," McGraw-Hill (1969).
9. M. W. Cappiello, "Assessment of the Annular Mist Interfacial Shear in TRAC-PF1/MOD1 Against Downcomer Bypass and Tieplate Flooding Data," ASME Winter Meeting, New Orleans, Louisiana (December 1984).
10. I. Kataoka and M. Ishii, "Mechanism and Correlation of Droplet Entrainment and Deposition in Annular Two-Phase Flow," Argonne National Laboratory report ANL-82-44, NUREG/CR-2885 (July 1982).
11. Y. Taitel and A. E. Dukler, "A Model for Predicting Flow Regime Transitions in Horizontal and Near Horizontal Gas-Liquid Flow," AIChE Journal 22, No. 1, 47-55 (1976).
12. A. Ohnuki, "Experimental Study of Countercurrent Two-Phase Flow in a Horizontal Tube Connected to an Inclined Riser," J. Nucl. Sci. Technol. (to be published).

NOMENCLATURE

A	:	flow area
C_i	:	interfacial shear coefficient
D_d	:	droplet diameter
D_h	:	hydraulic diameter
E	:	fraction of liquid entrained as droplets
g	:	acceleration caused by gravity
h_ℓ	:	collapsed liquid height
J^*	:	dimensionless velocity based on the CCFL correlation by Wallis
j	:	superficial velocity
Re_ℓ	:	Reynolds number of liquid phase
V_c	:	critical gas velocity
V_E	:	minimum gas velocity required for entrainment
V	:	average velocity
We	:	Weber number of droplets
We_e	:	Weber number of entrainment
ρ	:	density
σ	:	surface tension
θ	:	inclination angle of flow path from the horizontal
μ_ℓ	:	viscosity of liquid
α	:	void fraction in test tubes
δ	:	liquid film thickness

Subscripts

ℓ	:	liquid phase
g	:	gas phase
d	:	droplet

TABLE I

MAIN DIMENSIONS OF TRAC INPUT MODELS

Groups/Items	Diam. (m)	Length (m)	Theta (Deg)	$Diam._1$ (m)	$Length_1$ (m)	$Diam._2$ (m)	Ref. No.
Vertical tubes	0.025	0.05	90	0.2	0.9	0.2	(2)
	0.0254	1.52	90	0.33	0.71	0.33	(1)
	0.152	3.66	90	0.543	1.15	0.66	(1)
Inclined tubes	0.026	0.1	20	0.4	0	0.3	(12)
	0.026	0.11	40	0.4	0	0.3	(12)
	0.026	0.16	60	0.4	0	0.3	(12)
Horizontal tube	0.072	0	0	0.4	1.18	0.42	(4)
Inclined riser tube with horizontal tube (simulated hot leg)	0.026	0.038	40	0.4	0.19	0.3	(12)

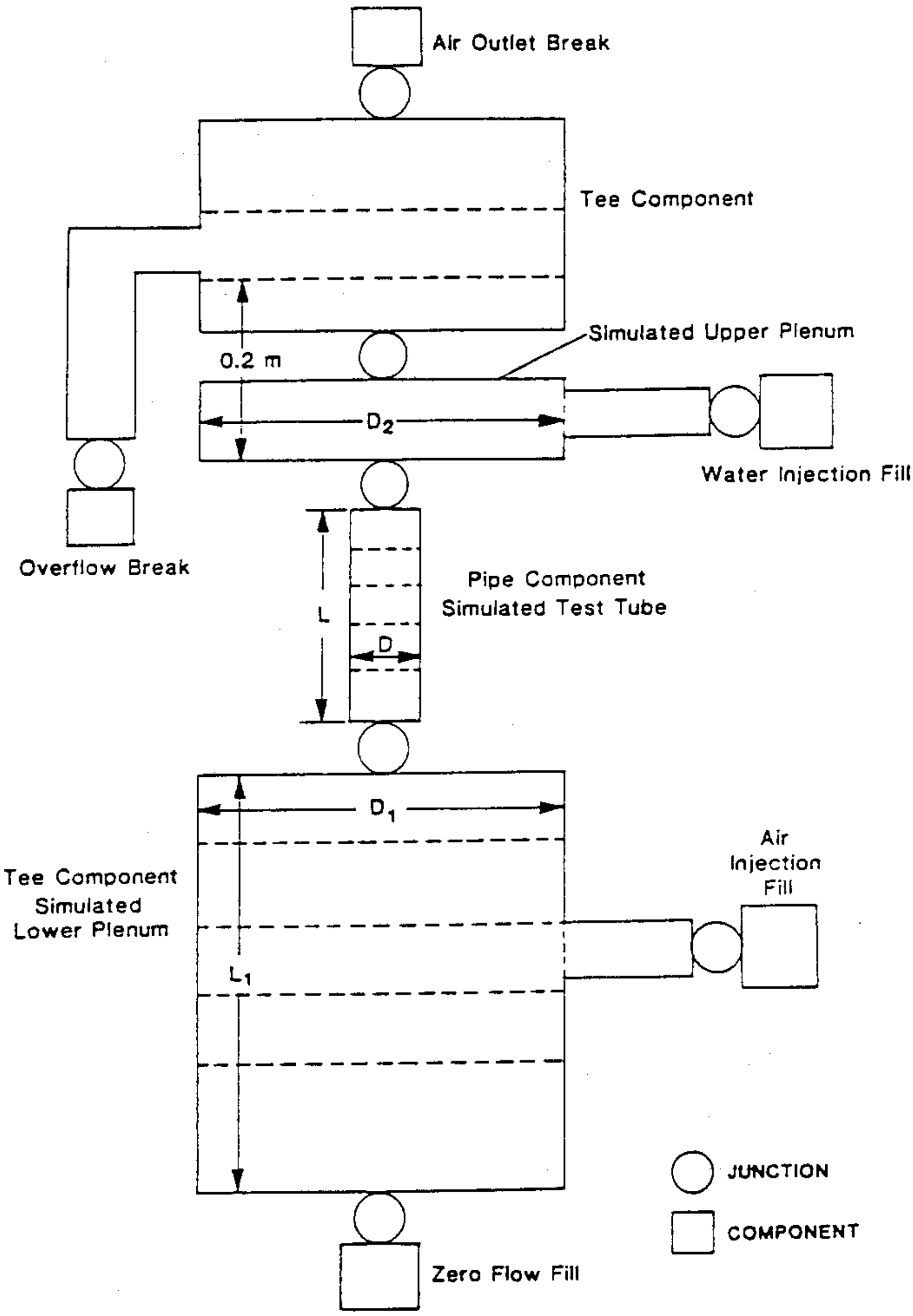

Fig. 1 TRAC input model for the vertical pipe experiments

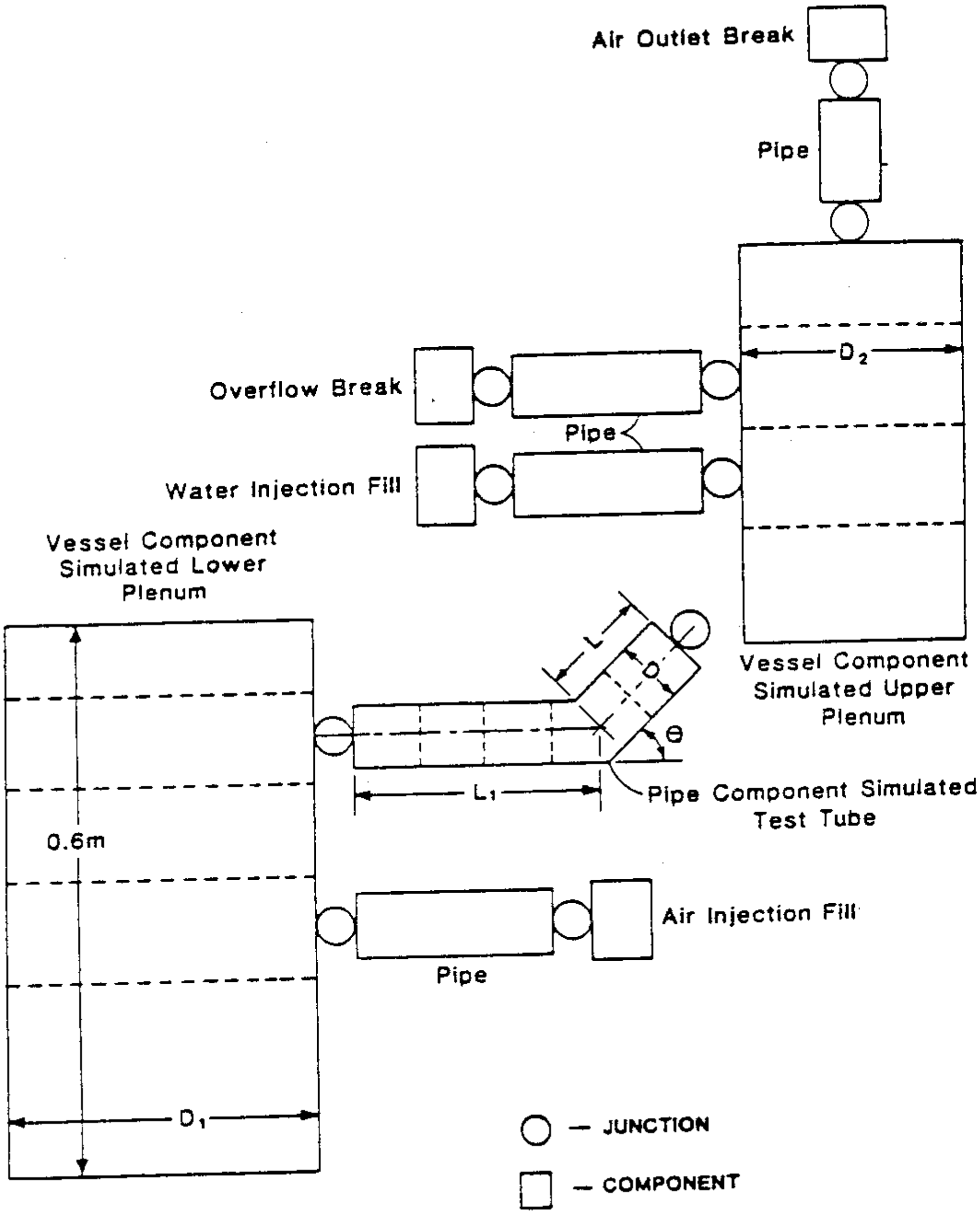

Fig. 2 TRAC input model for the horizontal and inclined pipe experiments

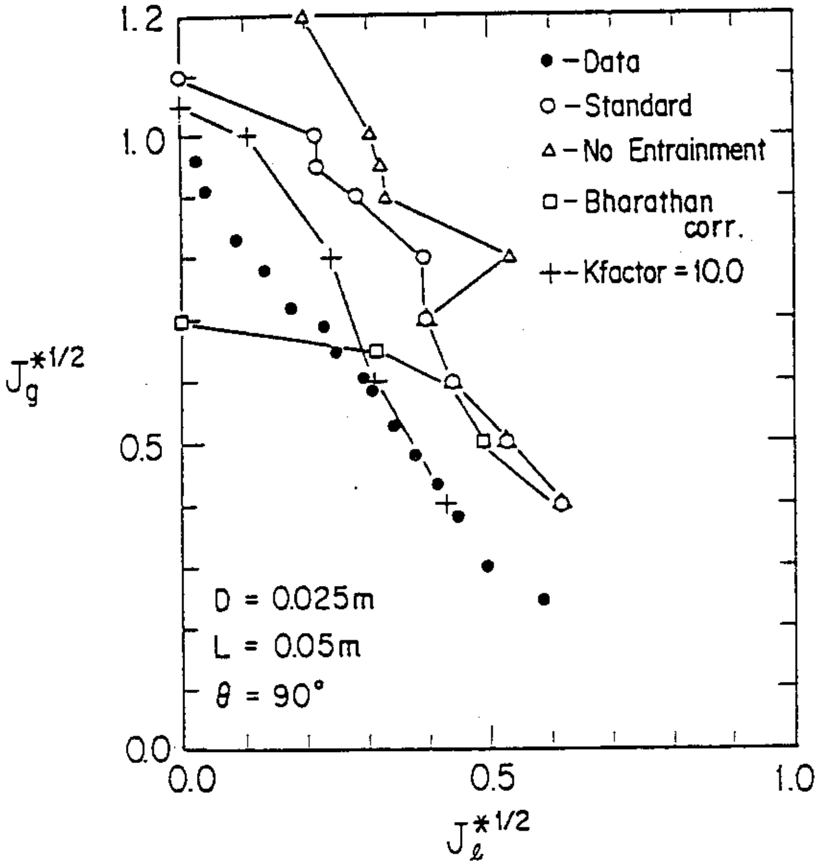

Fig. 3(a) Comparison of TRAC-PF1/MOD1 results with vertical pipe CCFL data, D = 0.025 m, L = 0.05 m.

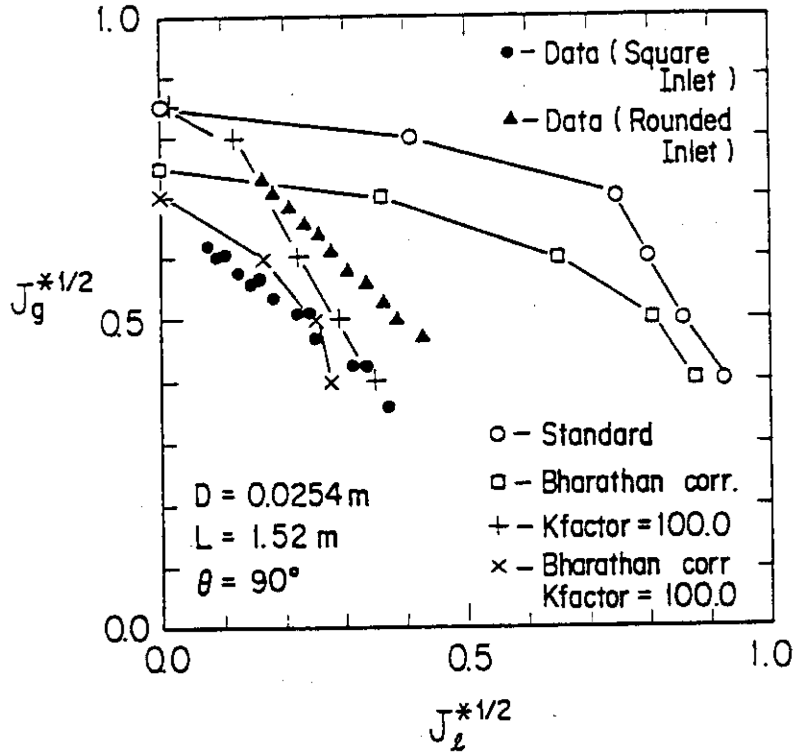

Fig. 3(b) Comparison of TRAC-PF1/MOD1 results with vertical pipe CCFL data, D = 0.0254 m, L = 1.52 m.

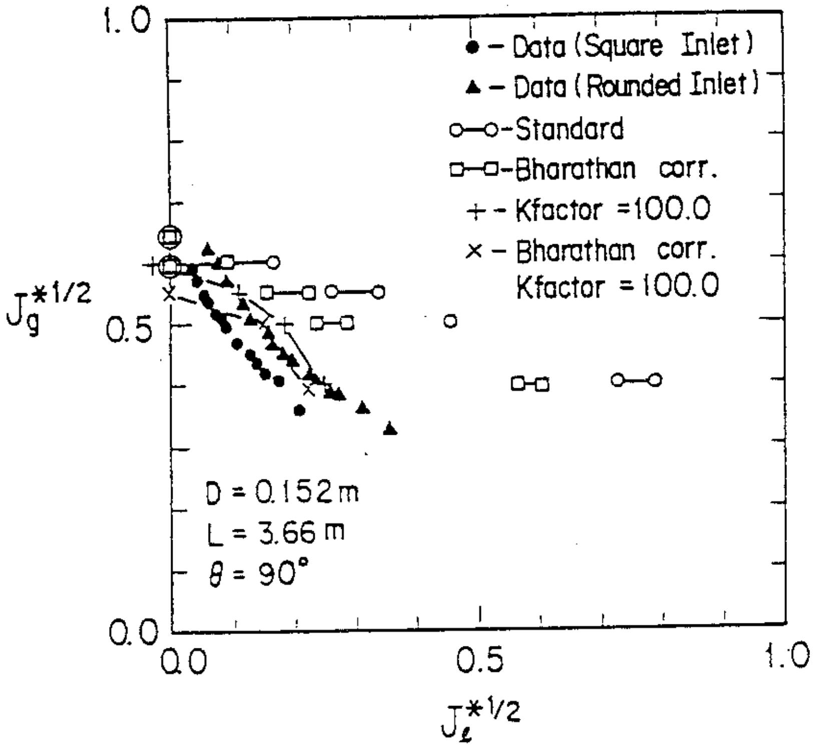

Fig. 3(c) Comparison of TRAC-PF1/MOD1 results with vertical pipe CCFL data, D = 0.152 m, L = 3.66 m.

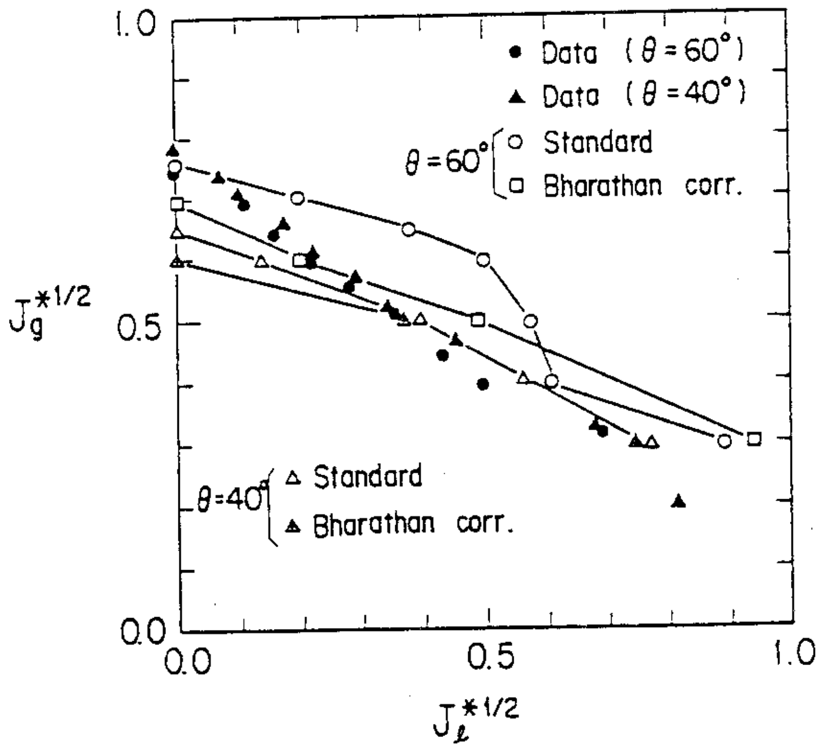

Fig. 4 Comparison of TRAC-PF1/MOD1 results with CCFL data for a pipe inclined at angles of 40° and 60° from the horizontal.

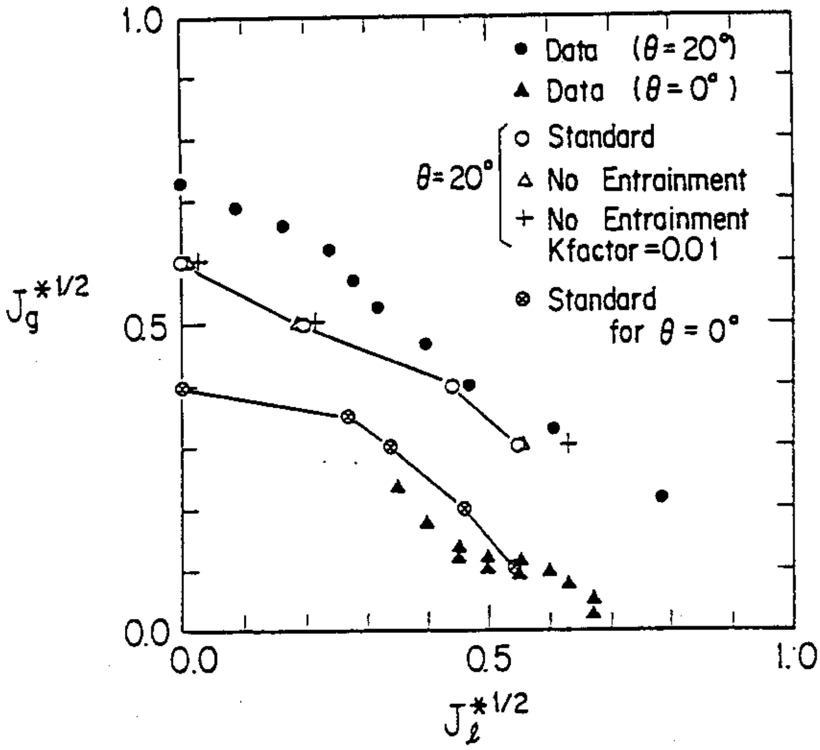

Fig. 5 Comparison of TRAC-PF1/MOD1 results with CCFL data for a pipe inclined at angles of 20° and 0° from the horizontal.

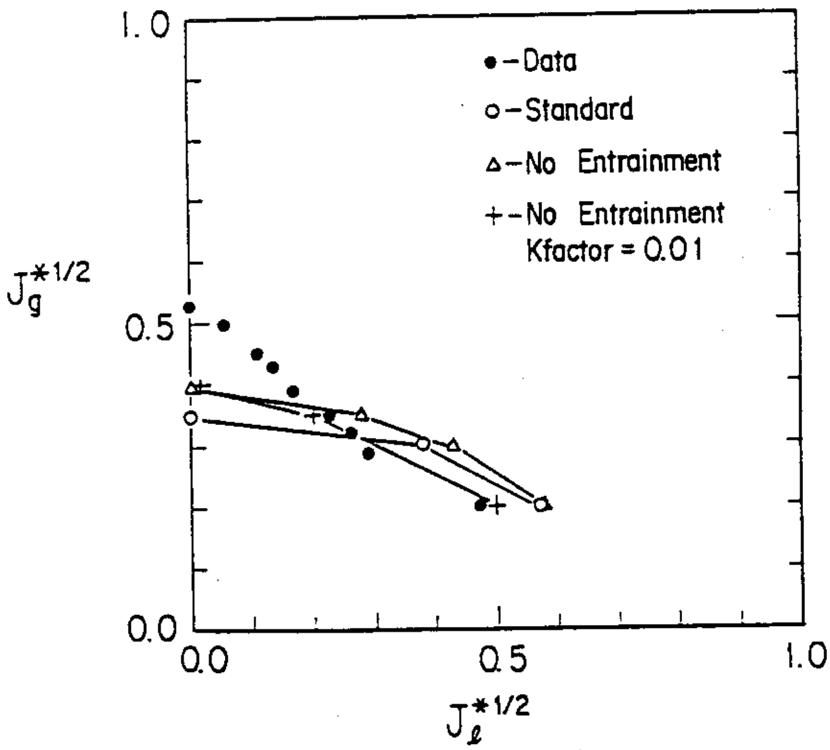

Fig. 6 Comparison of TRAC-PF1/MOD1 results with CCFL data for a simulated PWR hot leg.