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TRAC-PF1 CHOKED-FLOW MODEL*

by

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ABSTRACT

The two-phase, two-component choked-flow model implemented in the latest version of the Transient Reactor Analysis Code (TRAC-PF1) was developed from first principles using the characteristic analysis approach. The subcooled choked-flow model in TRAC-PF1 is a modified form of the Burnell model. In this paper we discuss these choked-flow models and their implementation in TRAC-PF1. Comparisons using the TRAC-PF1 choked-flow models are made with the Burnell model for subcooled flow and with the homogeneous-equilibrium model (HEM) for two-phase flow. These comparisons agree well under homogeneous conditions. Generally good agreements have been obtained between the TRAC-PF1 results from models using the choking criteria and those using a fine mesh (natural choking). Code-data comparisons between the separate-effects tests of the Marviken facility and the Edwards' blowdown experiment also are favorable.

NOMENCLATURE

a = sound speed (ms^{-1})
C = virtual mass coefficient
p = pressure (Pa)
s = specific entropy ($Jkg^{-1}K^{-1}$)
t = time (s)
V = velocity (ms^{-1})
x = distance (m)

Greek Symbols

α = gas (air-vapor mixture) volume fraction
λ = characteristic root
ρ = density (kgm^{-3})

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*Work performed under the auspices of the US Nuclear Regulatory Commission.

Subscripts

a = air (noncondensable gas)
c = cell center
e = cell edge
g = gas (air-vapor mixture)
HE = homogeneous equilibrium
i = characteristic index
ℓ = liquid
m = air-vapor-liquid mixture
max = maximum
re = real part of a complex number
s = saturation
v = water vapor

Superscripts

n = time level
$\bar{\ }$ = vector

I. INTRODUCTION

The Transient Reactor Analysis Code (TRAC) is an advanced best-estimate systems code for analyzing postulated accidents in light-water reactors. The latest released version of the code, TRAC-PF1 (Ref. 1), provides this analysis capability for pressurized-water reactors (PWRs) and for a wide variety of thermal-hydraulic experimental facilities.

Because the TRAC-PF1 fluid-dynamics equations for one-dimensional components use a multistep procedure that allows the material Courant condition to be violated, the choking calculations can be done simply by using a sufficiently fine mesh for components with smooth area changes. However, the TRAC-PF1 quasi-steady choked-flow model saves computational time because it allows a much coarser mesh. For components with abrupt area changes, a one-dimensional fine mesh can cause erroneous natural-choking results. For all such cases, a separate choking model is almost a necessity. Thus, a choking model not only improves computational efficiency but also accounts for effects such as sharp area changes, surface roughness, and three-dimensional modeling, etc.

Section II describes the TRAC-PF1 choked-flow model. Section III compares this model with other conventional models and the experimental data. Section IV discusses the important conclusions.

II. MODEL

A. Two-Phase-Flow Choking Criterion

The TRAC-PF1 two-phase choking model is an extension of one developed by Ransom and Trapp[2] that incorporates an additional inert gas component. As suggested by Ransom and Trapp, we assume that thermal equilibrium exists between the phases. The validity of this assumption has not been investigated in the presence of an inert gas. However, this assumption is not an inherent feature of the TRAC-PF1 model and can be changed easily, if necessary.

The two-fluid flow field under thermal equilibrium is described by the inert gas continuity equation, the overall continuity equation, two phasic momentum equations, and the mixture energy equation. When the nondifferential source terms are omitted (because they do not enter into characteristic analysis), the equations are

$$\frac{\partial}{\partial t}(\alpha\rho_a) + \frac{\partial}{\partial x}(\alpha\rho_a V_g) = 0 \quad , \tag{1}$$

$$\frac{\partial\rho_m}{\partial t} + \frac{\partial}{\partial x}(\rho_m V_m) = 0 \quad , \tag{2}$$

$$\begin{aligned} &\alpha\rho_g\left[\frac{\partial V_g}{\partial t} + V_g\frac{\partial V_g}{\partial x}\right] + \alpha\frac{\partial p}{\partial x} \\ &\quad + C\alpha(1-\alpha)\rho_m\left[\frac{\partial V_g}{\partial t} + V_\ell\frac{\partial V_g}{\partial x} - \frac{\partial V_\ell}{\partial t} - V_g\frac{\partial V_\ell}{\partial x}\right] = 0 \quad , \end{aligned} \tag{3}$$

$$\begin{aligned} &(1-\alpha)\rho_\ell\left[\frac{\partial V_\ell}{\partial t} + V_\ell\frac{\partial V_\ell}{\partial x}\right] + (1-\alpha)\frac{\partial p}{\partial x} \\ &\quad + C\alpha(1-\alpha)\rho_m\left[\frac{\partial V_\ell}{\partial t} + V_g\frac{\partial V_\ell}{\partial x} - \frac{\partial V_g}{\partial t} - V_\ell\frac{\partial V_g}{\partial x}\right] = 0 \quad , \end{aligned} \tag{4}$$

and

$$\frac{\partial}{\partial t}(\rho_m s_m) + \frac{\partial}{\partial x}\left[\alpha\rho_g V_g s_g + (1-\alpha)\rho_\ell V_\ell s_\ell\right] = 0 \quad . \tag{5}$$

The last terms in Eqs. (3) and (4) represent interphasic force terms caused by relative acceleration. These terms are discussed in detail in Refs. 3 and 4. Following Ransom and Trapp's formulation, the energy equation is written in the form of the mixture specific entropy that is conserved for adiabatic flow (neglecting irreversibilities associated with interphasic mass transfer and relative phase acceleration). However, no basic difficulty in the analysis is experienced if the mixture energy equation is written in terms of the internal energy or the enthalpy.

In the thermal-equilibrium case, ρ_a, ρ_v, ρ_ℓ, s_a, s_v, and s_ℓ are known functions of p_a and p_v. If we assume that Dalton's law of partial pressures applies, Eqs. (1)-(5) can be written in terms of the five unknowns p_a, p_v, α, V_g, and V_ℓ. The matrix representation of these equations is

$$A(\overline{U})\,\frac{\partial\overline{U}}{\partial t} + B(\overline{U})\,\frac{\partial\overline{U}}{\partial x} = 0 \quad , \tag{6}$$

where the vector $\overline{U}$ consists of p_a, p_v, α, V_g, and V_ℓ. The characteristic roots, λ_i, of the above system of equations are defined as the roots of the fifth-order polynomial,

$$\det\,(A\lambda + B) = 0 \quad . \tag{7}$$

Choking occurs when the signal propagating with the largest velocity relative to the fluid is stationary; that is, $\lambda_{i,re,max} = 0$. Equation 7 is extremely difficult to solve analytically. Thus, TRAC-PF1 obtains the characteristic roots of Eq. (7) numerically. This method advantageously maintains generality and facilitates computations under different assumptions. The next three paragraphs describe the calculational sequence for the TRAC-PF1 two-phase choking criterion.

1. Equation (7) for its solution requires p_a, p_v, α, ρ_a, ρ_v, ρ_ℓ, s_a, s_v, s_ℓ, and their derivatives to be specified at the cell edge where the choking criterion is applied. However, these quantities are known only at the cell center. Direct use of the cell-center quantities yields erroneous results

caused by the presence of steep gradients near the choking plane. Therefore, an estimate of the thermodynamic state at the cell edge is necessary. This is accomplished by assuming a constant entropy process between the cell center and the cell edge and by iterating for the cell-edge pressure to maximize the mass flux [a classical technique used in generating the homogeneous-equilibrium-model (HEM) tables]. In addition to the thermodynamic state at the cell edge, the foregoing technique also gives the homogeneous-equilibrium sound speed, a_{HE}, that is used as a first estimate for the largest characteristic root. (When the nonhomogeneous effects are not dominant, the desired root is close to the homogeneous-equilibrium sound speed.)

2. By maintaining a constant phase slip (V_g/V_ℓ), Eq. (7) yields intermediate time-level values of $V_g^{n+1/2}$ and $V_\ell^{n+1/2}$, so that $\lambda_{i,re,max} = 0$. The intermediate time-level mixture velocity, $V_m^{n+1/2}$, then is compared with the current value of the mixture velocity V_m. If $V_m^{n+1/2} < V_m$, the flow is choked.

3. By using V_g and V_ℓ when the flow is unchoked or $V_g^{n+1/2}$ and $V_\ell^{n+1/2}$ when the flow is choked, the TRAC hydrodynamic equations are solved. Their solution gives new time-step values, V_g^{n+1} and V_ℓ^{n+1}.

B. Subcooled Flow Choking Criterion

During the subcooled blowdown phase, the fluid undergoes a phase change at the break because the containment pressure is much less than the saturation pressure corresponding to the system fluid temperature. Thus, the choking velocity can be calculated using the Burnell model until a point is reached when the system pressure is so low that the cell-edge velocity, V_ℓ, is less than the homogeneous-equilibrium sound speed, a_{HE}. The subcooled choking criterion, therefore, is given by the maximum of the Burnell expression and the homogeneous-equilibrium sound speed. Thus,

$$V_\ell = \max \left\{a_{HE}, \left[V_c^2 + \frac{2(p_c - p_e)}{\rho_m}\right]^{1/2}\right\} \quad , \tag{8}$$

where the cell-edge pressure, p_e, can be considerably lower than the saturation pressure, p_s, because of thermal nonequilibrium caused by fast transients. A nucleation delay model developed by Jones[5] has been implemented in TRAC-PF1. This model gives $(p_s - p_e)$.

The calculational sequence is similar to that for the two-phase model. The homogeneous-equilibrium sound speed is calculated by maximizing the mass flux, as described in Sec. II.A. The only unknown is the liquid-phase choking velocity that is set explicitly using Eq. (8), which gives $V_\ell^{n+1/2}$.

III. RESULTS

In Sec. III.A, the TRAC-PF1 calculated results are compared with other conventional models under approximately homogeneous conditions to investigate the validity of the TRAC model under such conditions. Comparisons of the TRAC-PF1 choking calculations with models using fine mesh and the experimental data from some separate-effects facilities are given in Sec. III.B.

A. Comparisons with Other Models

The primary requirement for an accurate choked-flow model is that it yield results that are close to the homogeneous-equilibrium calculations when the flow approaches such a limit, because the nonhomogeneous effects are only of secondary importance in most situations. Therefore, the homogeneous-equilibrium sound speed calculated by TRAC-PF1 should agree with the true sound speed. Figure 1 shows a comparison of the homogeneous-equilibrium sound speed calculated by TRAC-PF1 with that obtained from the tables of D. G. Hall[6] for different void fractions at 560-K saturation temperature. The agreement between the calculations and the tables is excellent.

Figure 2 compares the TRAC-PF1 subcooled critical flow to the Burnell model and the HEM for stagnation pressures ranging from 7.1 MPa (saturated liquid) to 15.0 MPa (subcooled liquid) at a constant 560-K temperature. The Burnell model is the modified-Burnell model from RELAP4/MOD6, (Ref. 7) that accounts for nucleation delay by an empirical expression. The HEM mass flux represents a lower limit on the mass flux. As desired, the TRAC-PF1 model calculations give results that are similar to those for the Burnell model. The minor discrepancy between the TRAC-PF1 choked-flow and the Burnell models primarily is caused by the difference in the nucleation-delay models.

Figure 3 compares the TRAC-PF1 two-phase critical-flow model calculations with the HEM data at 560-K saturation temperature. The agreement again is good. The TRAC-PF1 calculations differ from the HEM data because the nonhomogeneous effects are not accounted for in the HEM. Larger differences

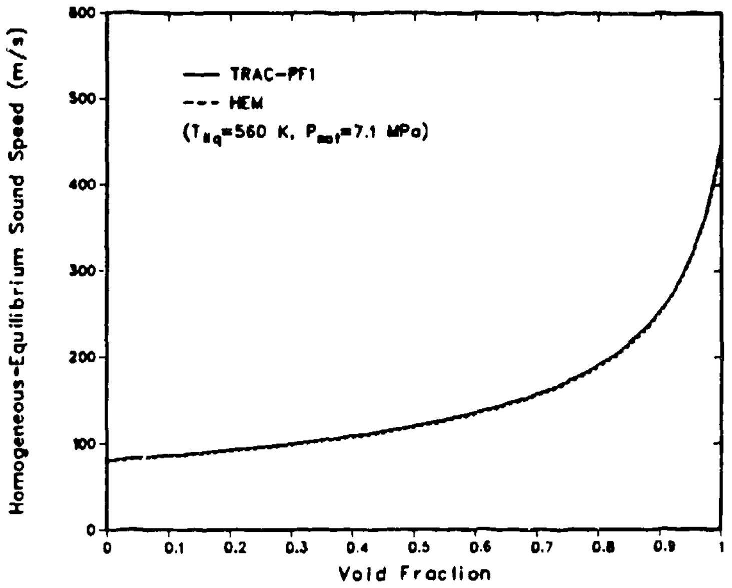

Fig. 1.
Comparison of the TRAC-PF1 two-phase homogeneous-equilibrium sound speed with that obtained from the tables.

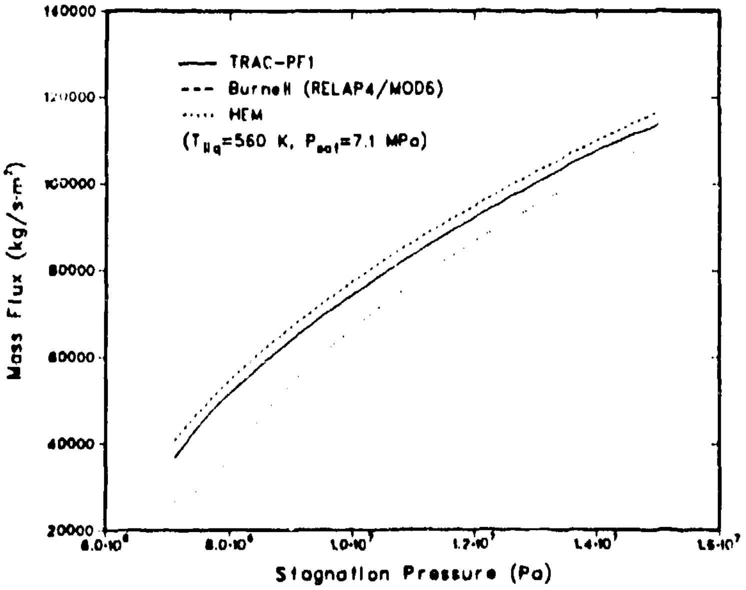

Fig. 2.
Comparison of the subcooled critical mass fluxes using the TRAC-PF1 calculations, the Burnell model, and the HEM tables.

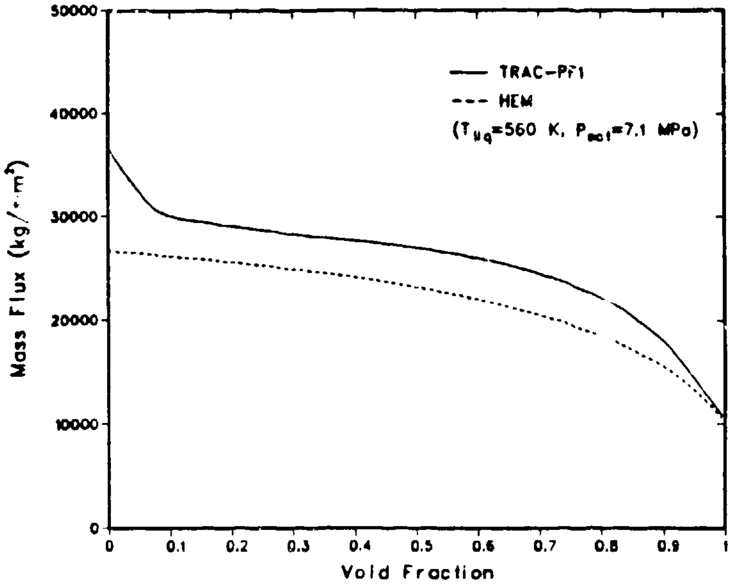

Fig. 3.
Comparison of the two-phase critical mass fluxes for the TRAC-PF1 calculations and the HEM tables.

between the results obtained from the two models are expected when the upstream phasic velocities differ. (The flow upstream of the break was assumed to be stagnant for this calculation.)

B. Comparisons with Fine-Mesh Calculations and the Experimental Data

A true test of the accuracy of a choking model is its ability to predict results similar to those obtained using an extremely fine mesh (natural choking) for geometries with smooth area changes. Therefore, the TRAC-PF1 choking calculations are compared with the fine-mesh results and the experimental data from Tests 4 (Ref. 8) and 24 (Ref. 9) of the Marviken test facility and the Edwards' blowdown experiment.[10]

1. Marviken Test Facility. The Marviken full-scale critical-flow tests assess the ability of computer codes to predict large pressure-vessel blowdowns. The four major components of this facility are a pressure vessel, originally designed to be part of the Marviken nuclear power plant; a discharge pipe; a test nozzle with the minimum flow area in the system; and a rupture-disk assembly. Figure 4 shows the vessel that still includes part of the core superstructure and the moderator tank plus three gratings installed to

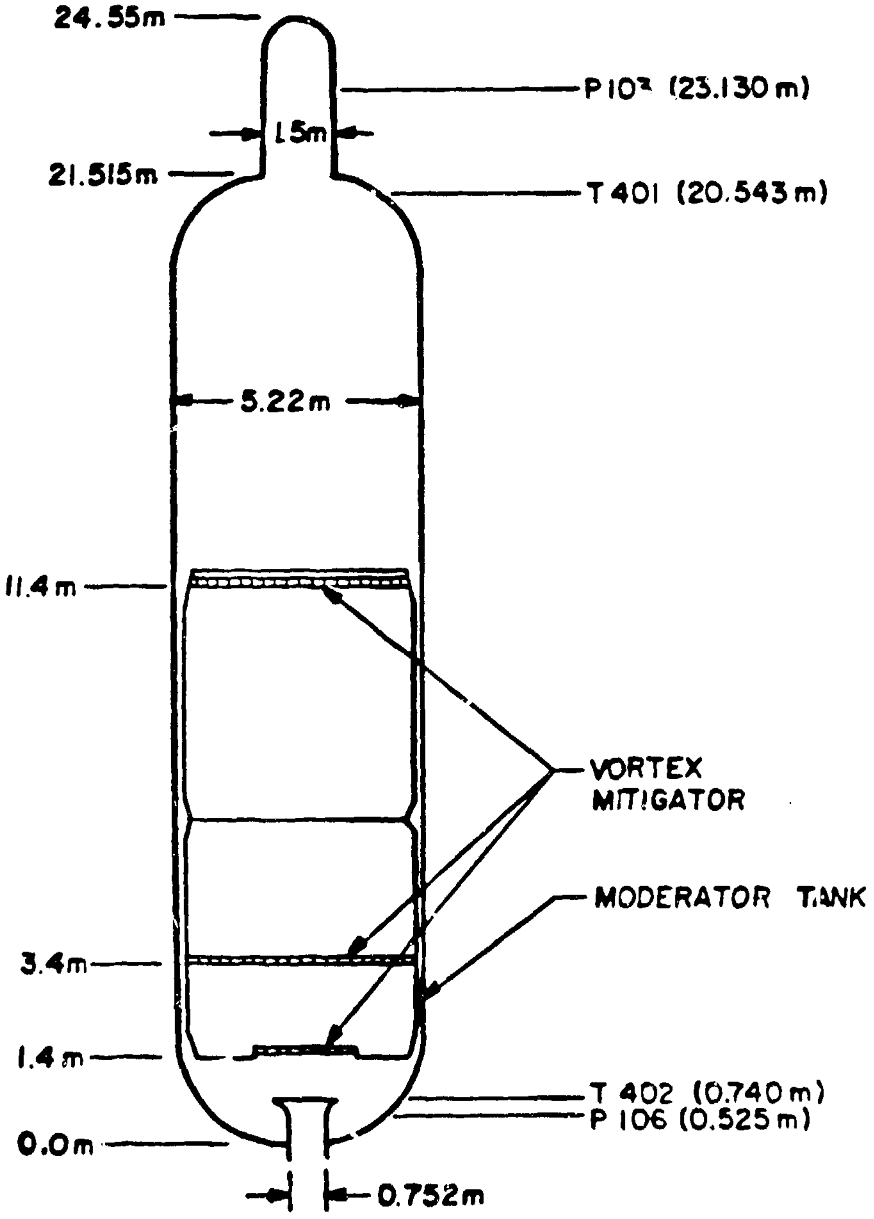

Fig. 4.
Marviken pressure vessel.

eliminate vortex formation. Figure 5 shows the other components. All elevations in both figures are measured relative to the vessel bottom. Pressure and temperature transducers are located along the vessel and the discharge pipe, as shown in Figs. 4 and 5. The signals from the various transducers are processed through a signal-conditioning unit with its channels connected to a pulse-code-modulation system.

Before a test is run, the vessel is partially filled with deionized water and heated by removing water from the vessel bottom, passing it through an electric heater, and returning it to the steam dome at the vessel top. This procedure produces a complicated initial temperature distribution in the vessel. A saturated steam dome fills the vessel region above the initial water level. The test is initiated by releasing the rupture disks and terminated by closing a ball valve in the discharge pipe. Marviken Tests 4 and 24 specifically were chosen because Test 4 had the longest nozzle and Test 24 had the shortest nozzle in the entire test series. The TRAC model for Marviken Tests 4 and 24 included four components. A zero-velocity FILL component modeled the vessel upper boundary. A PIPE component modeled the vessel above 2.6 m, including the maximum diameter region plus the top cupola. Another PIPE component modeled the lower part of the vessel, the discharge pipe, the nozzle, and the rupture-disk assembly. A BREAK component provided a pressure boundary condition at the rupture-disk-assembly lower boundary. For the fine-noding cases, the nozzles were modeled with 30 cells (15 in the converging section and 15 in the straight portion with a minimum cell length of 0.025 m) for Test 4 and 12 cells (5 in the converging section and 7 in the straight portion with a minimum cell length of 0.02 m) for Test 24. When using the choked-flow model, the nozzles in both tests were modeled by only two cells, one in the converging section and the other one simulating the entire straight section, with the choked-flow model invoked at the downstream edge of the second cell.

Figure 6 shows the TRAC mass flows using the choking model and the fine noding compared with the experimental flows derived from velocity (pitot-static) and vessel differential-pressure measurements. The pitot-static data curve is valid throughout the transient, whereas the vessel differential-pressure curve is valid only after ~5 s. The choking calculation gives almost identical results to those for the fine-mesh case. Both the choked-flow and the fine-mesh calculations also agree well with the

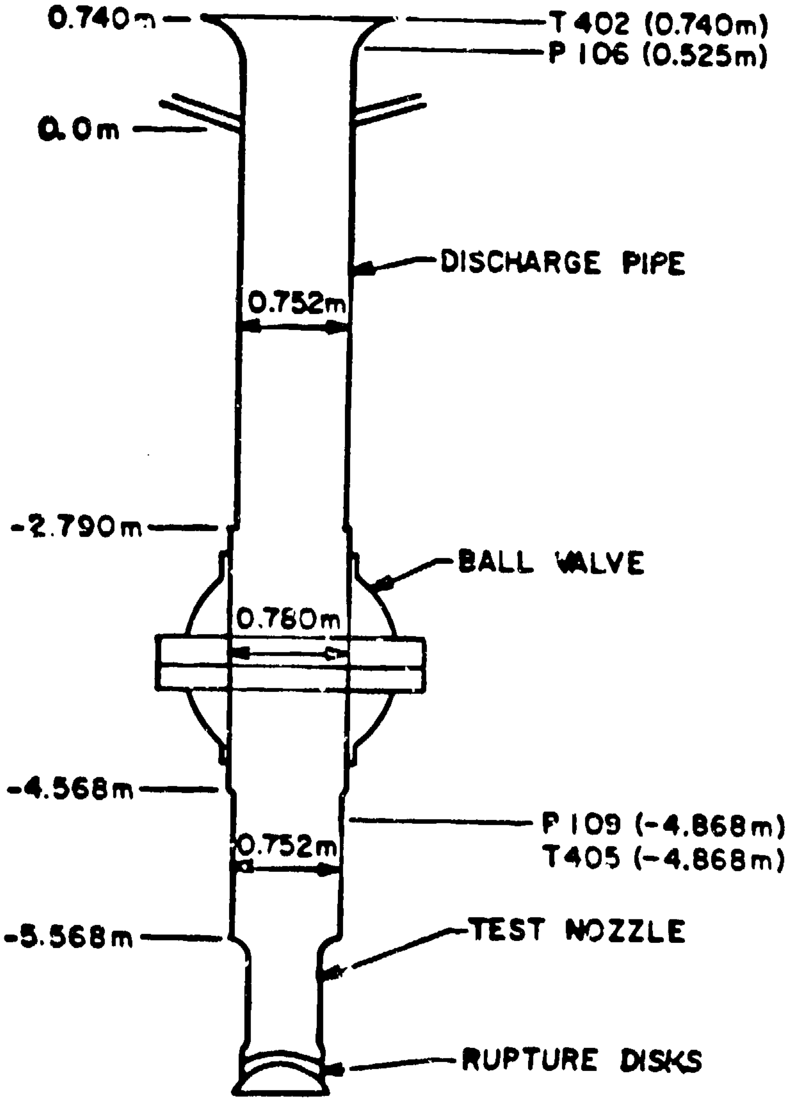

Fig. 5.
Marviken discharge pipe, test nozzle, and rupture-disk assembly.

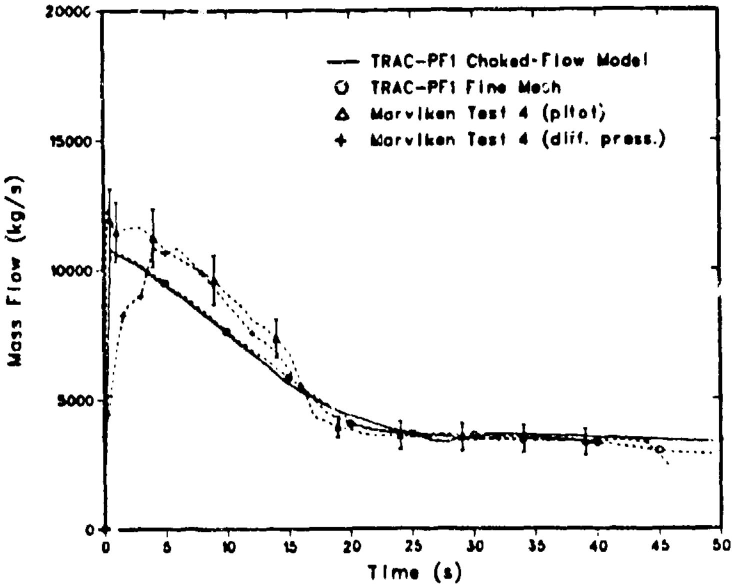

Fig. 6.
Comparison of the nozzle mass flows for Marviken Test 4 between the experimental data and the TRAC-PF1 models using fine-mesh and choking criteria.

experimental data except during the subcooled blowdown phase when the mass flow is underpredicted by an average of ~10%.

Figure 7 shows the mass flows for Test 24. The agreement between the choking calculation and the results obtained from the fine-mesh case is not as good as for Test 4. This discrepancy is attributed to the predominance of nonequilibrium effects between the phases caused by the short nozzle length. These nonequilibrium effects are not modeled in the TRAC-PF1 choking calculation. (The straight sections of the nozzles for Tests 4 and 24, respectively, were 1.5 and 0.166 m long with length-to-diameter ratios of 2.95 and 0.33.)

To investigate the importance of nonequilibrium effects in Test 24, a sensitivity run was made by moving the choking plane from the downstream to the upstream edge of the straight section. This is approximately equivalent to making the "frozen" assumption in the straight section instead of the thermal-equilibrium assumption. Figure 8 shows the curve for the new calculation, where the mass flow using the choking model is now overpredicted compared to the flow from the fine-mesh results. The assumption that thermal

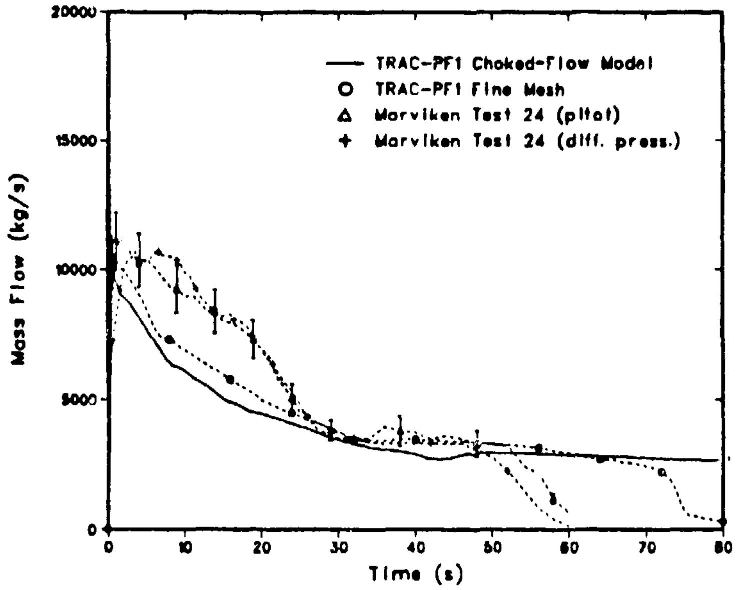

Fig. 7.
Comparison of the nozzle mass flows for Marviken Test 24 between the experimental data and the TRAC-PF1 models using fine-mesh and choking criteria.

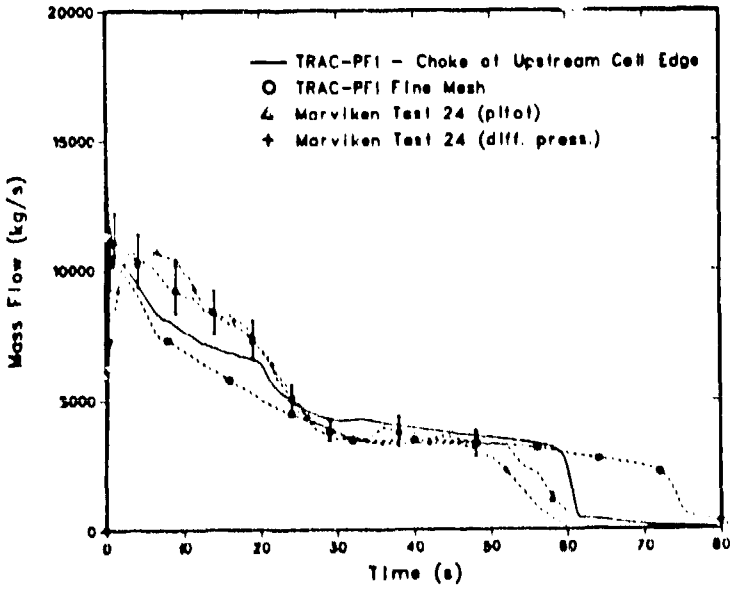

Fig. 8.
Comparison of the nozzle mass flows for Marviken Test 24 between the experimental data and the TRAC-PF1 models using fine-mesh and choking criteria at the upstream edge of the nozzle straight section.

equilibrium exists between the phases even in the absence of a noncondensable gas may not be valid under all situations.

2. Edwards' Blowdown Experiment. The Edwards' horizontal-pipe blowdown experiment studied depressurization phenomena of initially nonflowing subcooled water. The experimental apparatus consisted of a 4.096-m-long, straight, steel pipe with a 0.073-m inside diameter. The apparatus was designed for a maximum 17.24-MPa pressure at temperatures to 616.5 K. The discharge end of the horizontal pipe was sealed with a 0.0127-m-thick glass disk.

The pipe was filled with demineralized water; a hydraulic pump and a control valve regulated the system pressure. The pipe was evacuated by a vacuum pump before filling it with water. Before rupturing the glass disk, the pipe was isolated from the supply tank to prevent the discharge of cold water into the pipe during blowdown. Pressure transducers were located at gauge stations GS-1 to GS-7 and a temperature transducer was located at GS-5 (Fig. 9). Also provided at GS-5 were two aluminum alloy disk windows for transient void-fraction measurements, using an x-ray absorption system. The pipe was insulated and heated electrically. The operating procedure required that degassed water completely fill the pipe. The pipe was pressurized cold to ~25% above the initial depressurization 7-MPa test pressure and checked for

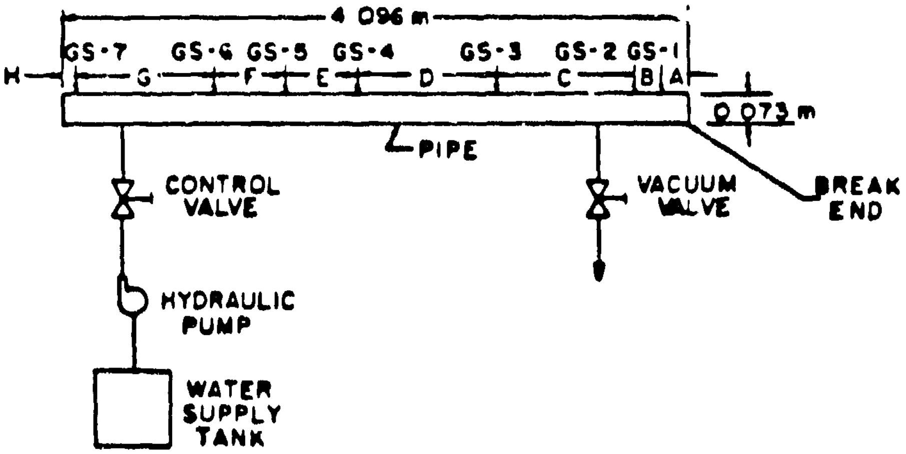

Fig. 9.
Schematic of Edwards' horizontal-pipe blowdown experiment (adapted from Ref. 10).

leaks. Next, the pressure was reduced to 3.45 MPa and heat was applied gradually for ~1.5 h. During the heating of the water, the system pressure was maintained at ~3.45 MPa above the saturation pressure to prevent liquid flashing. The temperature variation along the pipe was limited by adjusting the voltage control for each heater. The system initially was brought to an approximately uniform 515-K temperature and 7-MPa pressure. Because the isolating valve between the pipe and storage tank closed, the glass disk ruptured and the data were recorded automatically.

The TRAC model consisted of a zero-velocity FILL component to simulate the closed end of the pipe, two PIPE components coupled in series, and a BREAK component. Near the discharge end of the pipe, the minimum cell lengths were 0.00509 m for the fine-mesh case, and 0.17325 m for the choked-flow model. The choking model was invoked at the discharge end, which had the minimum cross-sectional area in the system.

Figure 10 shows the pressure histories near the middle of the pipe (GS-4). The agreement between the choking and the fine-mesh calculations again

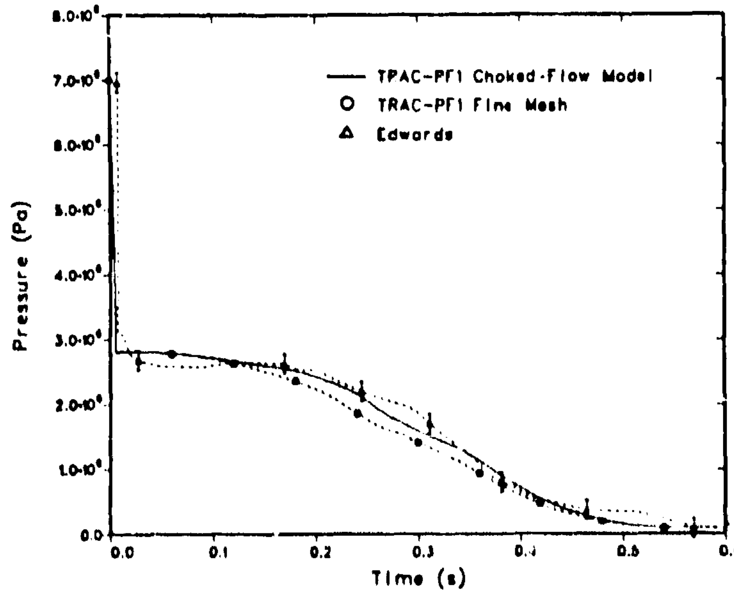

Fig. 10.
Pressure history comparison for Edwards' blowdown experiment between the experimental data and TRAC-PF1 calculations using fine-mesh and choking criteria.

is good with the choking calculational results being closer to the data than the fine-mesh results.

IV. CONCLUSIONS

The two-phase, two-component choked-flow model implemented in TRAC-PF1 was developed from first principles with a minimal amount of empiricism. The model assumes that thermal equilibrium exists between the phases in the presence or absence of an inert gas. The eigenvalues for the system of coupled differential equations are obtained numerically. This generality gives the user the freedom to investigate and incorporate differential equations derived under different assumptions. The model yields results similar to those obtained using a fine mesh for components with smooth area changes. However, the quantitative agreement with the fine-mesh calculations is deficient for Marviken Test 24, which has a short nozzle, because the equilibrium assumption may be improper in that case. The results also compare well with other conventional models (the modified Burnell and the HEM). A good mass flow comparison between the TRAC-PF1 two-phase model and the HEM was obtained because the upstream fluid was stagnant, which gives minimal nonhomogeneous effects. However, for other two-phase situations, where the upstream liquid and vapor velocities differ significantly from each other, the nonhomogeneous effects may be very important. Comparisons of the TRAC-PF1 calculations with the data from the separate-effects Marviken tests and Edwards' blowdown experiment also were favorable.

Next, the choked-flow comparisons with the air-water experimental data from facilities such as Moby Dick will be made to investigate the validity of the thermal-equilibrium assumption in the presence of a noncondensable gas. It is suspected that the equilibrium assumption in this case may be even more restrictive than that in the absence of a noncondensable gas. Further comparisons with the data in the absence of a noncondensable gas also are needed to explore fully the applicability of the model. If a frozen model is found to predict the results of the experimental data more accurately in a number of situations, it also will be implemented in TRAC-PF1.

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