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CRITICAL EQUILIBRIUM INHOMOGENEOUS TWO-PHASE TWO-COMPONENT WATER–STEAM–AIR FLOW

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Abstract—A mathematical model is derived of a steady-state, two-phase, two-component adiabatic flow consisting of water–steam–air under the condition of thermodynamic equilibrium. The idea is used of a quasi-constant slip. An expression is found for the value of the critical mass flow rate. The program CRITFLOW-2PH2C has been created based on the model. The given numerical examples illustrate the applicability of the model to tubes with arbitrary length.

NOMENCLATURE

a, velocity of sound;
c_p, specific heat at constant pressure;
D_h, hydraulic diameter;
d, total differential;
G, mass flow rate;
G^*, critical mass flow rate;
g, gravitational acceleration;
h, specific enthalpy;
n, polytropic exponent;
p, pressure;
$\dot{q}'''$, thermal power supplied to a unit volume of flow;
R_g, R_L, gas constants;
R, pressure loss per unit length due to friction;
T, absolute temperature;
w, velocity;
x, quality;
z, linear coordinate.

Greek symbols
α, void fraction;
κ, isentropic exponent;
λ, eigenvalue;
μ, amount of generated steam per unit time per unit volume of flow;
ρ, density;
τ, time;
φ, angle between the upward directed vertical and flow direction.

Subscripts and superscripts
L, air;
D, steam;
f, water;
$''$, saturated steam;
$'$, saturated water;
ex, phase which yields mass;
p, constant pressure;
fr, friction.

1. INTRODUCTION

WE HAVE reported [1] a model of a transient, 1-dim., two-phase, two-component flow consisting of water, steam and air under the following assumptions:

(a) equal pressure of the two phases;
(b) the two components of the gas phase, air and steam, obey Dalton's law;
(c) equal temperatures of the two phases;
(d) equal velocities of the two phases;
(e) in the presence of water the steam is always saturated with respect to the corresponding temperature of the system;
(f) the air is assumed to be a single noncondensable ideal gas;
(g) constant cross-section of the channel.

The system of four partial differential equations

$$\frac{\partial T}{\partial \tau} + w\frac{\partial T}{\partial z} + \frac{B}{A}\frac{\partial w}{\partial z} = \frac{\dot{q}'''}{A}, \quad (1)$$

$$\frac{\partial p}{\partial \tau} + w\frac{\partial p}{\partial z} + \rho a^2\frac{\partial w}{\partial z} = \frac{C}{A}\dot{q}''', \quad (2)$$

$$\frac{\partial w}{\partial \tau} + w\frac{\partial w}{\partial z} + \frac{1}{\rho}\frac{\partial p}{\partial z} = -\frac{Z}{\rho}; \quad Z = \rho g \cos\varphi + R, \quad (3)$$

$$\frac{\partial \rho}{\partial \tau} + w\frac{\partial \rho}{\partial z} + \rho\frac{\partial w}{\partial z} = 0, \quad (4)$$

where

$$C = p_L\left[\frac{1}{T} + \frac{1}{p_L}\frac{dp''_D}{dT} + \frac{1-\alpha}{\alpha}\frac{1}{\rho_f}\frac{\partial \rho_f}{\partial T}\right], \quad (5)$$

$$E = \alpha\rho_L\frac{\partial h_L}{\partial p_L} + (1-\alpha)\rho_f\frac{\partial h_f}{\partial p} - 1, \quad (6)$$

$$D = \alpha\left[\rho_L\left(\frac{\partial h_L}{\partial T} - \frac{\partial h_L}{\partial p_L}\frac{dp''_D}{dT}\right) + \rho''_D\frac{dh''_D}{dT}\right] + (1-\alpha)\rho_f \times \frac{\partial h_f}{\partial T} + \frac{h''_D - h_f}{v''_D - v_f}\left(\frac{\alpha}{\rho''_D}\frac{d\rho''_D}{dT} + \frac{1-\alpha}{\rho_f}\frac{\partial \rho_f}{\partial T}\right), \quad (7)$$

$$A = CE + D, \quad (8)$$

$$B = \frac{h''_D - h_f}{v''_D - v_f} - \frac{p_L}{\alpha}E, \quad (9)$$

$$\rho a^2 = CB/A + p_L/\alpha, \quad (10)$$

$$\rho = \alpha(\rho''_D + \rho_L) + (1-\alpha)\rho_f \quad (11)$$

has the eigenvalues

$$\lambda_{1,2} = w; \quad \lambda_{3,4} = w + a \quad (12\text{–}15)$$

where a is the velocity of sound. The critical mass flow rate is equal to

$$G^* = \rho a. \quad (16)$$

When applying this model to the analysis of the propagation of LOCA inside the rooms of a nuclear power plant with water-cooled reactors, the question often arises of determining the critical mass flow rate of an inhomogeneous two-phase flow under the above assumptions about the thermodynamic state of the flow. The aim of the present work is to formulate such a model for a critical inhomogeneous two-phase, two-component flow consisting of water–steam–air at thermodynamic equilibrium.

2. MODEL

We choose as dependent variables the pressure p, the temperature T, the mass flow rate G, and the quality x. In accordance with the assumptions made above in Section 1, we use the equations of state given in Appendix 1. From Dalton's law it follows that

$$\alpha_L = \alpha_D = \alpha. \quad (17)$$

We use the following system as the starting point of our considerations:

$$\frac{d}{dz}(\alpha\rho_L w_g) = 0, \quad (18)$$

$$\frac{d}{dz}(\alpha\rho''_D w_g) = \mu, \quad (19)$$

$$\frac{d}{dz}[(1-\alpha)\rho_f w_f] = -\mu, \quad (20)$$

$$\frac{d}{dz}[\alpha\rho_g w_g^2 + (1-\alpha)\rho_f w_f^2] + \frac{dp}{dz} = -Z; \; Z = [\alpha\rho_g + (1-\alpha)\rho_f]g\cos\varphi + R, \quad (21)$$

$$\alpha\rho_L w_g \frac{ds_L}{dz} = \frac{\dot{q}'''_L}{T}, \quad (22)$$

$$\alpha\rho''_D w_g \frac{ds''_D}{dz} = \frac{1}{T}[\dot{q}'''_D + \mu(h_{ex} - h''_D)], \quad (23)$$

$$(1-\alpha)\rho_f w_f \frac{ds_f}{dz} = \frac{1}{T}[\dot{q}'''_f - \mu(h_{ex} - h_f)]. \quad (24)$$

We note that no substantial terms in the steady-state mass and momentum conservation equations (18)–(21) are neglected. Further we introduce the following definitions for the relative mass flow rates for gas x, air x_L, and steam x_D

$$x_L G = \alpha\rho_L w_g, \quad (25)$$

$$x_D G = \alpha\rho''_D w_g, \quad (26)$$

$$(1-x)G = (1-\alpha)\rho_f w_f, \quad (27)$$

in the two-phase flow. From these definitions the following equations follow:

$$x = x_L + x_D, \quad (28)$$

$$x_D = x\rho''_D/\rho_g, \quad (29)$$

$$x_L = x\rho_L/\rho_g. \quad (30)$$

Making use of these definitions, we obtain the following form for the system (18)–(24):

$$\frac{d}{dz}(x_L G) = 0, \quad (31)$$

$$\frac{d}{dz}(x_D G) = \mu, \quad (32)$$

$$\frac{d}{dz}[(1-x)G] = -\mu, \quad (33)$$

$$\frac{d}{dz}(G^2 v_I) + \frac{dp}{dz} = -Z, \quad (34)$$

$$x_L G \frac{ds_L}{dz} = \frac{\dot{q}'''_L}{T}, \quad (35)$$

$$x_D G \frac{ds''_D}{dz} = \frac{1}{T}[\dot{q}'''_D + \mu(h_{ex} - h''_D)], \quad (36)$$

$$(1-x)G \frac{ds_f}{dz} = \frac{1}{T}[\dot{q}'''_f - \mu(h_{ex} - h_f)], \quad (37)$$

where

$$v_I = v_S f_1 \quad (38)$$

$$v_S = x v_g + S(1-x)v_f \quad (39)$$

$$f_1 = [1 + x(S-1)]/S \quad (40)$$

$$S = w_g/w_f \quad (41)$$

Summing up the three mass conservation equations we get

$$dG/dz = 0 \quad \text{or} \quad G = \text{const}. \quad (42)$$

Using equation (42) and summing up the three entropy conservation equations we get

$$\left.\begin{array}{l} G\dfrac{dx_D}{dz} = \mu \\ G\dfrac{dx}{dz} = \mu \end{array}\right\} \quad \frac{dx_D}{dz} = \frac{dx}{dz}, \quad (43)$$

$$G^2\frac{dv_I}{dz} + \frac{dp}{dz} = -Z \quad (44)$$

$$GT\left[x_L\frac{ds_L}{dz} + x_D\frac{ds''_D}{dz} + (1-x)\frac{ds_f}{dz}\right] = \dot{q}''' - \mu(h'' - h_f), \quad (45)$$

$$x_L = \text{const.} \quad (46)$$

For an adiabatic flow

$$\dot{q}''' = 0 \quad (47)$$

we obtain

$$\frac{dx_D}{dz} = \frac{dx}{dz}, \quad (48)$$

$$G^2 \frac{dv_I}{dz} + \frac{dp}{dz} = -Z, \quad (49)$$

$$T\left[x_L \frac{ds_L}{dz} + x_D \frac{ds_D''}{dz} + (1-x)\frac{ds_f}{dz}\right] = -\frac{dx}{dz}(h'' - h_f). \quad (50)$$

We transform the momentum equation in the following way

$$\frac{dp}{dz} = -Z/(1 - G^2/G^{*2}) \quad (51)$$

where

$$G^{*2} = -(dv_I/dp)^{-1}. \quad (52)$$

The calculation of dv_I/dp is shown in Appendix 2. After some transformations of equations (43) and (45)

$$\frac{d}{dz}\left(x\frac{\rho_D''}{\rho_g}\right) = \frac{dx}{dz}$$

or

$$x\frac{d}{dz}\left(\frac{\rho_D''}{\rho_g}\right) = \frac{\rho_L}{\rho_g}\frac{dx}{dz}$$

or

$$x_L \frac{d\rho_D''}{dz} - x_D \frac{d\rho_L}{dz} = \rho_L \frac{dx}{dz}, \quad (53)$$

$$\frac{1}{h_D'' - h_f} \times \Bigg\{\underbrace{\left[x_L\left(c_{pL} + v_L\frac{d\rho_D''}{dT}\right) + x_D T\frac{ds_D''}{dT} + (1-x)c_{pf}\right]}_{c_p} \times \frac{dT}{dz} - x_L\frac{TR_L}{p_L}\frac{dp}{dz}\Bigg\} = -\frac{dx}{dz}, \quad (54)$$

after substituting the equation of state into equation (53), and after solving with respect to dT/dp and dx/dp, we obtain

$$\frac{dT}{dp} = \left(\frac{x_D}{R_L T} + \frac{x_L}{h_D'' - h_f}\right) \Bigg/ \left[x_L\frac{d\rho_D''}{dT} + x_D\left(\frac{\rho_L}{T} + \frac{1}{R_L T}\frac{dp_D''}{dT}\right) + \frac{\rho_L c_p}{h_D'' - h_f}\right], \quad (55)$$

$$\frac{dx}{dp} = \left(x_L/\rho_L - c_p\frac{dT}{dp}\right)\Bigg/(h_D'' - h_f). \quad (56)$$

Let us now check equations (55) and (56) by obtaining the known relations for the known limiting cases. Thus for $x_L = 1$, $x_D = 0$ we obtain

$$\frac{dT}{dp} = \frac{1}{c_p\rho_L} \quad (57)$$

$$\frac{dx}{dp} = 0 \quad (58)$$

and for $x_L = x_D = 0$

$$\frac{dT}{dp} = 0, \quad (59)$$

$$\frac{dx}{dp} = -\frac{c_{pf}}{h_D'' - h_f}\frac{dT}{dp}. \quad (60)$$

These relations are well-known in the thermodynamics of one-component fluids, for a one-component adiabatic flow of air and a one-component adiabatic flow of liquid water, respectively.

3. CRITICAL TWO-PHASE, TWO-COMPONENT, INHOMOGENEOUS FLOW

Thus, the equilibrium steady-state, two-phase, two-component, isentropic flow consisting of water, steam and air is described in the inhomogeneous case by the following system of ordinary non-linear differential equations:

$$G = \text{const.}, \quad (42)$$

$$x_L = \text{const.}, \quad (61)$$

$$x_D = x\rho_D''/\rho_g, \quad (29)$$

$$\frac{dp}{dz} = -Z/(1 - G^2/G^{*2}); \quad Z = \rho g\cos\varphi + R, \quad (51)$$

$$\frac{dT}{dz} = \frac{dT}{dp}\frac{dp}{dz}; \quad \frac{dT}{dp} = \left(\frac{x_D}{R_L T} + \frac{x_L}{h_D'' - h_f}\right) \Bigg/ \left[x_L\frac{d\rho_D''}{dT} + x_D\left(\frac{\rho_L}{T} + \frac{1}{R_L T}\frac{dp_D''}{dT}\right) + \frac{\rho_L c_p}{h_D'' - h_f}\right] \quad (62), (55)$$

$$\frac{dx}{dz} = \frac{dx}{dp}\frac{dp}{dz}; \quad \frac{dx}{dp} = (x_L/\rho_L - c_p\, dT/dp)/(h_D'' - h_f) \quad (63), (56)$$

where

$$\rho = \alpha(\rho'' + \rho_L) + (1-\alpha)\rho_f \quad (64)$$

$$c_p = x_L\left(c_{pL} + v_L\frac{dp_D''}{dT}\right) + x_D T\frac{ds_D''}{dT} + (1-x)c_{pf}. \quad (65)$$

If $G = G^*$, we obtain $dp = -\infty$, i.e. we have a critical flow. Equation (52) defines the local critical mass flow rate. It should be noted that the assumption we made for the adiabatic two-phase flow ($\dot{q}''' = 0$) does not imply that $\dot{q}_g''' = 0$, i.e. the gas phase undergoes a polytropic change of state. This is shown in Appendix 3.

A simplified formula for dv_1/dp is given in Appendix 3. Perhaps the assumption that $n \sim$ const. and that 'the gaseous mixture has the properties of an ideal gas' might be considered a strong restriction. However in practice with a discrete integration of the system (51), (62), (63) along the tube, the use of (A3–9) without using equation (62) speeds up calculations without influencing the accuracy as compared with the direct integration of (51), (62), (63). This is explained as follows:

(1) the RHSs of the system (51), (62), (63) are kept constant within one linear step Δz during integration by any method. This is equivalent to the assumption that $n \sim$ const;

(2) n is a relatively slowly changing quantity close to unity and is calculated in each new point as a function of the actual parameters of state.

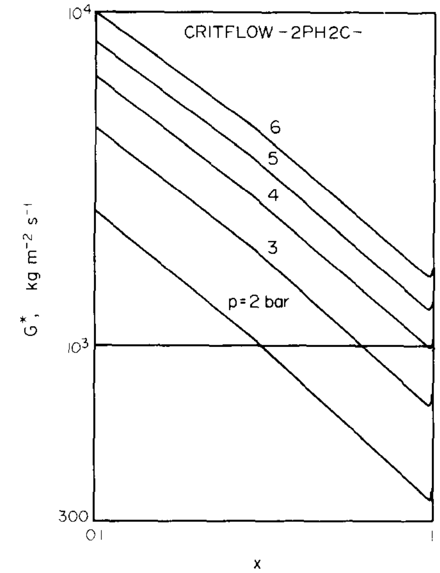

FIG. 1. The critical mass flow rate as a function of the quality and pressure. $L/D = 5$, $D = 0.5$ m, $T_{en} = 372.78$ K.

4. SOME NUMERICAL EXAMPLES AND APPLICATION OF THE METHOD

Thus, the system of differential equations (51), (62), (63) together with the conditions (42), (61), (29), the adequate empirical slip correlation [2], an appropriate correlation for the loss of pressure due to friction [3], a suitable set of approximations for the thermophysical properties [4] and an integration procedure represent a stationary model of a two-phase, two-component flow with the already stated simplifying assumptions for tubes with arbitrary dimensions and a constant cross-section. If by varying G at the given initial conditions (p, T, x) at the tube entrance we obtain $dp = -\infty$ at the exit, then the flow in the tube is a critical one. The program CRITFLOW-2PH2C (Fortran 4, IBM 370/145) is created based on this model. The integration of the system (51), (62), (63) is done in the program using Euler's method with a step diminishing in a geometrical progression. Some results from calculations with CRITFLOW-2PH2C are shown in Figs. 1–3. They illustrate the dependence of the critical mass flow rate G on the most significant parameters. In all the figures the critical mass flow rate G is shown as a function of the quality x at the entrance of the tube and a variable parameter shown in Table 1.

The examples from Figs. 1–3 illustrate the applicability of the model to tubes of arbitrary length. This model can be classified substantially by introducing a noncondensable gas in the theory of the equilibrium inhomogeneous two-phase flow with a quasi-constant slip [5]. In the absence of steam, the model has the properties characteristic of an inhomogeneous non-equilibrium two-phase flow, concerning the critical mass flow rate. At small air content it has the properties typical of an equilibrium inhomogeneous two-phase flow.

This model has been successfully used in modelling the critical and subcritical flows between particular volumes of a NPS with a WWER during a LOCA.

Table 1

Fig. 1	$G = f(p_{en}, x_{en}, T_{en} = \text{const.}$	$L/D = \text{const.})$
Fig. 2	$G = f(T_{en}, x_{en}, p_{en} = \text{const.},$	$L/D = \text{const.})$
Fig. 3	$G = f(L/D, x_{en}, p_{en} = \text{const.},$	$T_{en} = \text{const.})$

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APPENDIX 1

$$\rho_L = \frac{p_L}{R_L T};$$

$$d\rho_L = \frac{1}{R_L T} dp_L - \frac{\rho_L}{T} dT = \underbrace{\frac{1}{R_L T}}_{\left(\frac{\partial \rho_L}{\partial p}\right)_T} dp - \underbrace{\left(\frac{\rho_L}{T} + \frac{1}{R_L T}\frac{dp''_D}{dT}\right)}_{+\ \frac{\partial \rho_f}{\partial p}} dT \quad \text{(A1-1)}$$

$$R_L = 287.1\,[\mathrm{J\,kg^{-1}\,K^{-1}}] \quad \text{(A1-2)}$$

$$\rho_D = \rho''_D(T) \qquad d\rho_D = \frac{d\rho''_D}{dT} dT \quad \text{(A1-3, 4)}$$

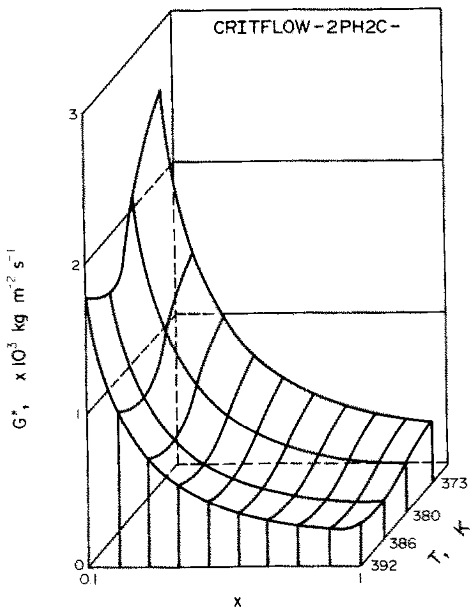

FIG. 2. The critical mass flow rate as a function of the quality and temperature. $L/D = 5$, $D = 0.5$ m, $p_{en} = 2$ bar.

$$\rho_f = \rho_f(T, p) \quad d\rho_f = \frac{\partial \rho_f}{\partial T} dT + \frac{\partial \rho_f}{\partial p} dp \qquad \text{(A1-5, 6)}$$

$$p_D = p_D''(T) \qquad dp_D = \frac{dp_D''}{dT} dT \qquad \text{(A1-7, 8)}$$

$$p_L = p - p_D'' \quad dp_L = dp - \frac{dp_D''}{dT} dT \quad \text{(A1-9, 10)}$$

$$\rho_g = \rho_D'' + \rho_L$$

$$d\rho_g = \underbrace{\frac{1}{R_L T}}_{\left(\frac{\partial \rho_g}{\partial p}\right)_T} dp + \underbrace{\left(\frac{d\rho_D''}{dT} - \frac{1}{R_L T}\frac{dp_D''}{dT} - \frac{\rho_L}{T}\right)}_{\left(\frac{\partial \rho_g}{\partial T}\right)_p} dT \qquad \text{(A1-11, 12)}$$

$$s_D'' = s_D''(T) \quad ds_D'' = \frac{ds_D''}{dT} dT \qquad \text{(A1-13, 14)}$$

$$s_f = s_f(T, p) \quad ds_f = \frac{c_{pf}}{T} dT - \left(\frac{\partial v_f}{\partial T}\right)_p dp \sim \frac{c_{pf}}{T} dT \quad \text{(A1-15, 16)}$$

$$s_L = s_L(T, p) \quad ds_L = \frac{c_{pL}}{T} dT - \frac{R_L}{p_L} dp_L = \left(\frac{c_{pL}}{T} + \frac{R_L}{p_L}\frac{dp_D''}{dT}\right) dT - \frac{R_L}{p_L} dp \quad \text{(A1-17, 18)}$$

APPENDIX 2

Since

$$v_t = v_t(p, T, x, S = \text{const.}), \qquad \text{(A2-1)}$$

$$\frac{dv_t}{dp} = \left(\frac{\partial v_t}{\partial p}\right)_{T,x} + \left(\frac{\partial v_t}{\partial T}\right)_{p,x}\frac{dT}{dp} + \left(\frac{\partial v_t}{\partial x}\right)_{p,T}\frac{dx}{dp} \qquad \text{(A2-2)}$$

holds, where

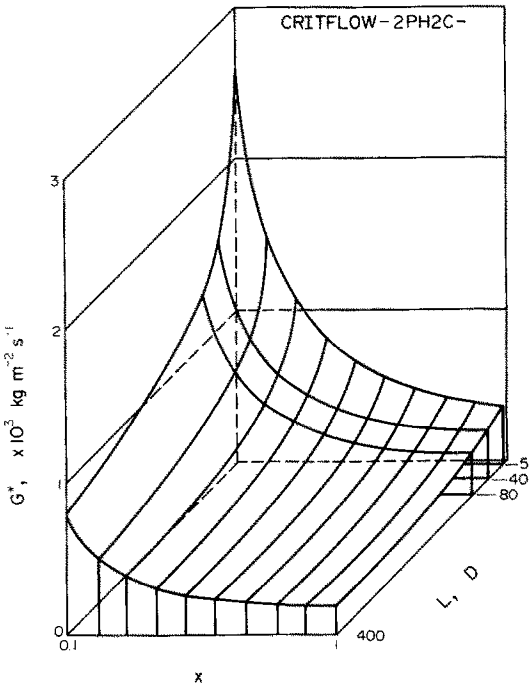

FIG. 3. The critical mass flow rate as a function of the quality and relative length. $T_{in} = 372.78$ K, $p_{en} = 2$ bar, $D = 0.5$ m.

$$\left(\frac{\partial v_t}{\partial p}\right)_{T,x} = f_1\left[x\left(\frac{\partial v_g}{\partial p}\right)_T + S(1-x)\left(\frac{\partial v_f}{\partial p}\right)_T\right], \qquad \text{(A2-3)}$$

$$\left(\frac{\partial v_t}{\partial p}\right)_{p,x} = f_1\left[x\left(\frac{\partial v_g}{\partial T}\right)_p + S(1-x)\left(\frac{\partial v_f}{\partial T}\right)_p\right], \qquad \text{(A2-4)}$$

$$\left(\frac{\partial v_t}{\partial x}\right)_{p,T} = f_1(v_g - Sv_f) + v_S(S-1)/S, \qquad \text{(A2-5)}$$

$$\left(\frac{\partial v_g}{\partial p}\right)_T = -\frac{1}{\rho_g^2}\left(\frac{\partial \rho_g}{\partial p}\right)_T = -\frac{1}{\rho_g^2}\frac{1}{R_L T}, \qquad \text{(A2-6)}$$

$$\left(\frac{\partial v_g}{\partial T}\right)_p = -\frac{1}{\rho_g^2}\left(\frac{\partial \rho_g}{\partial T}\right)_p = -\frac{1}{\rho_g^2}\left(\frac{d\rho_D''}{dT} - \frac{1}{R_L T}\frac{dp_D''}{dT} - \frac{\rho_L}{T}\right), \qquad \text{(A2-7)}$$

$$\frac{dp_D''}{dT} = \frac{1}{T}\frac{h_D'' - h'}{v_D'' - v'} = f(T). \qquad \text{(A2-8)}$$

APPENDIX 3

Presenting equation (55) in the form (A3-1)

$$\frac{dT}{T} = \frac{n-1}{n}\frac{dp}{p} \qquad \text{(A3-1)}$$

where

$$n = \left\{1 - \frac{p}{T}\left(\frac{x_D}{R_L T} + \frac{x_L}{h_D'' - h_f}\right)\Big/\left[x_L\frac{d\rho_D''}{dT} + x_D\left(\frac{\rho_L}{T} + \frac{1}{R_L T}\frac{dp_D''}{dT}\right) + \frac{\rho_L c_p}{h_D'' - h_f}\right]\right\}^{-1} > 1 \qquad \text{(A3-2)}$$

and assuming

$$n \sim \text{const.} \qquad \text{(A3-3)}$$

we obtain after integration

$$\frac{T}{T_0} = \left(\frac{p}{p_0}\right)^{(n-1)/n} \qquad \text{(A3-4)}$$

Defining the gas constant

$$R_g = p_0 v_{g0}/T_0 \qquad \text{(A3-5)}$$

and assuming that the gas phase behaves as a perfect gas

$$pv_g = R_g T \qquad \text{(A3-6)}$$

we get for equation (A3-4)

$$\frac{v_{g0}}{v_g} = (p/p_0)^{1/n} \qquad \text{(A3-7)}$$

or after differentiation

$$\frac{dv_g}{dp} = -\frac{v_g}{np}. \qquad \text{(A3-8)}$$

Using the last equation, equation (A2-2) can be written in the following way:

$$\frac{dv_l}{dp} = \frac{1}{S}[1 + x(S-1)]\left\{-\frac{xv_g}{np} + S(1-x)\left[\left(\frac{\partial v_f}{\partial p}\right)_T + \left(\frac{\partial v_f}{\partial T}\right)_p \frac{n-1}{n}\frac{T}{p}\right] + (v_g - Sv_f)\frac{dx}{dp}\right\} + [xv_g + S(1-x)v_f]\frac{S-1}{S}\frac{dx}{dp}. \qquad \text{(A3-9)}$$

EQUILIBRE CRITIQUE DANS UN ECOULEMENT DIPHASIQUE A DEUX COMPOSANTS VAPEUR–EAU–AIR

Résumé—Un modèle mathématique est construit pour un écoulement permanent, adiabatique, diphasique, á deux composants, soit eau–vapeur–air, sous les conditions d'un équilibre thermodynamique. On utilise l'idée d'un glissement quasi-constant. On trouve une expression pour la valeur du débit massique critique. Le programme CRITFLOW-2PH2C est basé sur ce modèle. Les exemples numériques donnés montrent l'applicabilité du modèle aux tubes de longeuer arbitraire.

ZUR KRITISCHEN INHOMOGENEN GLEICHGEWICHTS-ZWEIPHASENSTRÖMUNG VON WASSER-DAMPF-LUFT-GEMISCHEN

Zusammenfassung—Für eine stationäre adiabate Zweiphasen-Zweikomponenten-Strömung von Wasser, Dampf und Luft wird für thermodynamisches Gleichgewicht ein mathematisches Modell abgeleitet. Dabei wird die Vorstellung eines quasi-konstanten Schlupfes benutzt. Für den Wert der kritischen Massenstromdichte wird eine Beziehung gewonnen. Auf der Basis des Modells wurde das Programm CRITFLOW-2PH2C entwickelt. Die angeführten numerischen Beispiele zeigen die Anwendbarkeit des Modells auf Rohre willkürlicher Länge.

КРИТИЧЕСКОЕ ТЕЧЕНИЕ РАВНОВЕСНОЙ НЕОДНОРОДНОЙ ДВУХФАЗНОЙ ДВУХКОМПОНЕНТНОЙ СМЕСИ ВОДЯНОЙ ПАР-ВОЗДУХ

Аннотация—Предложена математическая модель стационарного адиабатического течения двухфазной двухкомпонентной смеси водяного пара и воздуха в условиях термодинамического равновесия. В основе модели лежит понятие квазипостоянного скольжения. Получено выражение для определения величины критического массового расхода. На основе модели разработана программа CRITFLOW-2PH2C. Проведенные численные расчеты свидетельствуют о применимости модели к трубам произвольной длины.