THE 4TH INTERNATIONAL TOPICAL MEETING ON
NUCLEAR THERMAL HYDRAULICS, OPERATIONS AND SAFETY
April 6-8, 1994, Taipei, Taiwan

MODELLING OF A SINGLE-COMPONENT TWO-PHASE FLOW REGIME MAP IN A HORIZONTAL PIPE WITH ROD BUNDLES

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ABSTRACT

Many flow regime maps in current use for modelling two-phase flow with rod bundles were developed for adiabatic situations and without interface mass transfer being taken into account. This paper describes the development of a flow regime map which includes the modelling the mass transfer between the two phases. The model used is a modified form of the mechanistic model proposed by Osamusali and Chang [1]. The effect of interfacial mass transfer on flow regime transitions predicted by the new model is discused in detail in this paper.

INTRODUCTION

Realible predictions of two-phase flow phenomena encountered during loss of coolant accident in a nuclear power plant primary heat transport system are important in performing safety analysis. The modelling of the various two-phase flow regimes is an essential aspect in such analysis. Calculation of heat transfer and pressure drop under two-phase flow is not only dependent on the fluid properties and equipment characteristics ,but also on flow regimes.

Approaches to predicting flow regimes include modelling of the liquid and vapour as separate flow fields. The coupling of the flow fields is done through interfacial transfer of mass, momentum and energy. Such a two-fluid model has the advantage of allowing for unequal temperatures and velocities for the two phases. Examples of two-fluid models are given by Kocamustafaogullari [2].

A simple representation of flow regimes is usually in the form of maps in terms of gas and liquid velocities. In the literature, two-phase flow regime maps which include the effect of interfacial mass transfer are comparatively rare. Usually mass transfer effects are accounted for by the changing of the phase velocities in the direction normal to the mass transfer. Braber [3], for example, assumed that flow regime change as a result of condensation takes place because of (a) a decrease in the ratio of the shear force to the gravity force and (b) an increase in the ratio of the liquid and vapour fractions.

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Experimental investigations of flow regime transitions in a horizontal pipe with rod bundle have been performed by a number of researchers. Aly [4] studied the case of horizontal air-water flow in a pipe containing a 37-rod bundle by focusing on the interior subchannels. Krishnan and Kowalski [5] analysed the stratified-to-slug flow transition in a horizontal pipe containing a 7-rod bundle. Osamusali and Chang [1] investigated both theoretically and experimentally flow regime transitions in 37-rod bundle under adiabatic conditions. They included the effect of surface tension in the modelling the transition from stratified-to- intermittent flow.

In the present work,the mechanistic model proposed by Osamusali and Chang [1] is modified to include the presence of interfacial mass transfer.

FLOW REGIMES IN A HORIZONTAL PIPE

Typical flow regimes in a horizontal pipe are shown in Fig. 1 and can be classified as follows [6].

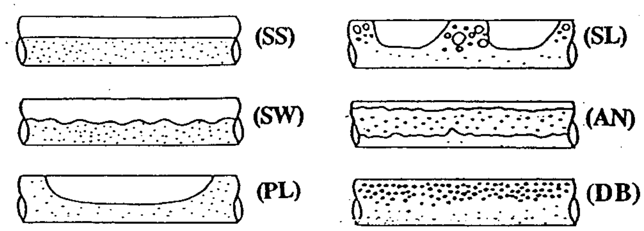

Figure 1 : Flow Regimes in a Horizontal Pipe

Stratified Smooth Flow (SS) is characterized by the liquid flowing along the bottom of the pipe and the gas flowing above it and the interface is smooth. At high gas flow rate, surface waves may be developed at the interface leading to a **Stratified Wavy Flow (SW)**.

Plug (PL) and Slug (SL) Flow are characterized by package of the liquid flowing down the pipe. If the packages are highly aerated with small bubbles, the flow is called Slug Flow. Plug Flow and Slug Flow are sometimes called as Intermittent Flow (IN).

Annular Flow (AN) is characterized by the gas flowing in the core while the liquid is flowing along the inner wall of pipe as a film.

Dispersed Bubble (DB) Flow is characterized by a train of discrete gas bubbles moving close to the upper wall of the pipe with the same velocity as the liquid.

ONE DIMENSIONAL TWO-FLUID MODEL

The flow situation used in the present analysis is shown in Fig.2. To derive the conservation equations, it is assumed that the cross-section of the duct is constant and the vapour is at saturation.

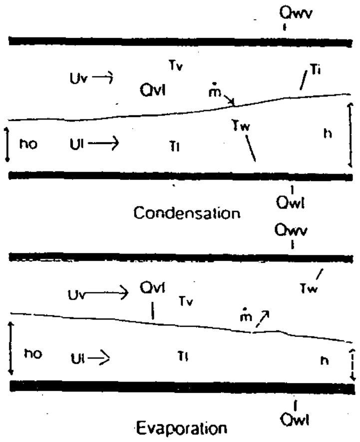

Figure 2: Flow Situation

The steady-state continuity equations for vapour and liquid phases can be written as follows

$$\rho_j \frac{d}{dz}(U_j A_j) = \beta \dot{m}, \quad j=v,l \quad (1)$$

The steady-state momentum equations for the vapour and liquid phases may be written as

$$\rho_j \frac{d}{dz}(U_j^2 A_j) = -A_j \frac{d}{dz}\Delta P_{ji} - A_j \rho_j g \frac{dh_l}{dz} - \tau_j S_j - \beta \tau_i S_i + \beta \dot{m}(U_i - U_j) \quad (2)$$

where j=v for vapour phase and j=l for liquid phase. In Eqns. 1 and 2, the parameter β = 1 for vapour phase and -1 for liquid phase, the interfacial velocity U_i equals $(U_l+U_v)/2$ [7], and the ΔP_{ji} equals to P_j-P_i.

The mixture momentum of both phases may be obtained by eliminating the pressure term in Eqn. 2 and using the following approximation ,

$$\Delta P_{vi} - \Delta P_{li} = \sigma \frac{\partial^2 h_l}{\partial z^2} - \left(\frac{\dot{m}}{S_i}\right)^2 \frac{(\rho_l - \rho_v)}{\rho_l \rho_v} \quad (3)$$

If we substitute Eqn. 3 into Eqn. 2, we obtain the following mixture momentum of the phases,

$$\begin{aligned} \rho_v U_v \frac{dU_v}{dz} - \rho_l U_l \frac{dU_l}{dz} = & -\frac{\rho_v U_v^2}{A_v}\frac{dA_v}{dz} \\ & + \frac{\rho_l U_l^2}{A_l}\frac{dA_l}{dz} - \sigma \frac{d^3 h_l}{dz^3} \\ & + 2\frac{(\rho_l - \rho_v)}{\rho_v \rho_l}\frac{\dot{m}}{S_i}\frac{d}{dz}\left(\frac{\dot{m}}{S_i}\right) \\ & + \left(\frac{U_i - U_v}{A_v} + \frac{U_i - U_l}{A_l}\right)\dot{m} \\ & - \left(\frac{1}{A_v} + \frac{1}{A_l}\right)\tau_i S_i - \frac{\tau_v S_v}{A_v} \\ & + \frac{\tau_l S_l}{A_l} + (\rho_l + \rho_v) g \frac{dh_l}{dz} \end{aligned} \quad (4)$$

Furthermore, by assuming that the liquid level varies only slowly with the axial distance z (excluding rapid condensation or evaporation), the derivative with respect to the axial distance z can be neglected compared to the other terms of Eqn. 4. Therefore, Eqn. 4 can be simplified to yield

$$\begin{aligned} & \tau_l \frac{S_l}{A_l} - \tau_v \frac{S_v}{A_v} - \tau_i S_i \left(\frac{1}{A_l} + \frac{1}{A_v}\right) \\ & + \dot{m}\left(\frac{U_i - U_v}{A_v} + \frac{U_i - U_l}{A_l}\right) = 0 \end{aligned} \quad (5)$$

The simplified conservation equations of energy for the liquid and vapour phases can be written as

$$\frac{d}{dz}(A_j T_j U_j) = \frac{Q_j}{\rho_j C_{pj}}, \quad j=l,v \quad (6)$$

where

$$Q_j = Q_{wj} S_{wj} + Q_{ij} S_i + Q_{bj} S_{bj} + Q_j'' A_j, \quad j=l,v \quad (7)$$

where C_{pl} and C_{pv} are the heat capacities for the liquid and vapour phases, respectively.

The left hand side of Eqn. 6 represents the axial gradient of energy transfer. The right hand side of Eqn. 7 represents the local heat flux terms. The heat flux terms are due to the transfer of sensible and latent heats to the liquid phase by the heated wall, vapour liquid interface and rod bundle, respectively. The last term in the right hand side of Eqn. 7 is the volumetric heat generation in the liquid and vapour phases.

CONSTITUTIVE EQUATIONS

To solve the governing equations, appropriate constitutive relationships are required. These include the interfacial mass, momentum and energy transfer, and shear stresses.

The shear stresses between the phases and the wall are represented by[6]

$$\tau_j = \frac{f_j \rho_j U_j |U_j|}{2} \qquad j=l,v \quad (8)$$

where f_l and f_v are the friction factors which may be expressed in the Blasius form for a smooth pipe,

$$f_l = C_l\left(\frac{D_l U_l}{\nu_l}\right)^{-n}, \quad f_v = C_v\left(\frac{D_v U_v}{\nu_v}\right)^{-m} \quad (9)$$

The hydraulic diameters in above equation may be written as follows: $D_l = 4\ A_l/S_l$, and $D_v = 4\ A_v/(S_v+S_l)$. The coefficients C_v and C_l are equal to 0.046 for turbulent flow and 16.0 for laminar flow, respectively. n and m take values of 0.2 for turbulent flow and 1.0 for laminar flow.

The interfacial momentum transfer between the vapour and the liquid is represented as

$$\tau_i = 0.5\ \rho_v\ f_i\ (U_v - U_l)|U_v - U_l| \quad (10)$$

where the interfacial friction factor is evaluated based on the given flow regimes. For stratified wavy and annular flow, it is assumed that the waves and ripples on the surface of the liquid are interpreted as roughness relative to the flow of the vapour. To account for this roughness the friction factor correlation proposed by Wallis [7] is used, $f_i = 0.02[1+75(\epsilon/D)]$. The roughness ($\epsilon$) is determined by applying the model proposed by Solbrig et al. [8].

The rate of mass transfer per unit length can be related to the interfacial heat flux using the following equation:

$$\dot{m} = \frac{S_i}{i_{lv}}[H_{iv}(T_v - T_i) + H_{il}(T_i - T_l)] \quad (11)$$

where T_i is the interfacial temperature. The coefficients, H_{il} and H_{iv}, are the interfacial heat transfer coefficients for interface-liquid and interface-vapour, respectively.

TRANSITION CRITERIA

(a) Transition from stratified smooth to wavy flow

According to Taitel and Dukler[6], wavy flow occurs when the force due to the gas flow is great enough to overcome the viscous force. Following this theory, the contribution of the mass transfer on the wave growth will be included in the present analysis.

Consider the surface wave profile to be $\eta = a \cos k(z-ct)$, where a is the average wave amplitude, c is the average wave velocity and k is wave number. The speed of the displacement of the surface normal to the interface can be written as $V_I = akc \sin k(z-ct)$ and the internal energy of the wave may be written as $W_{wave} = 1/2\ (\rho_l - \rho_v)ka^2c^2$.

According to Lamb[9], the viscous dissipation of energy per unit time per unit area may be written as $dW_{viss}/dt = -2\mu k^3c^2a^2$. In the case where there is a vapour stress on the surface of the wave, the vapour pressure acting on the wave makes a positive contribution only if it is acting at the same frequency as the wave. Using this postulate, Jeffreys[10] proposed that the rate of change of internal energy of the wave caused by the wind is $dW_{press}/dt = 1/2\ ck^2a^2s\rho_v\ (U_v - c)^2$.

The contribution of the mass transfer to the surface energy of the wave may be derived using mechanical energy jump at the interface that is by multiplying the pressure difference between the two phases due to the mass transfer and the velocity of the displacement normal to the interface. Due to the presence of the wave, the pressure due to the mass transfer can be broken up into Fourier components, one of which has the same frequency of the wave. Thus the pressure difference may be written as $P_{lv} = P_o\ ak \sin k(z-ct)$, where parameter P_o is $[(\rho_l - \rho_v)/\rho_l\rho_v](\dot{m}/S_i)^2$. By averaging the sinusoidal term, the rate of change of energy of the wave due to mass transfer per unit area may be written as $dW_{mass}/dt = 1/2\ P_o\ a^2k^2c$.

The condition of wave growth can be obtained using the relation, $dW_{wave}/dt = d(W_{viss} + W_{press} + W_{mass})\ /dt$. By assuming that $c^2 = g/k$, $da/dt \geq 0$ and for turbulent flow $c \approx U_l$, we obtain the following equation,

$$U_v^2 = \frac{g}{s\rho_v U_l}[4\nu(\rho_l - \rho_v) - M_a] \quad (12)$$

where M_a equals to P_oU_l/g.

(b) Transition from stratified to intermittent flow

Consider the wave profile as shown in Figure 3. The condition for wave growth may be written as,

$$P_i - P_i' > (h_l' - h_l)(\rho_l - \rho_v)g + \sigma\frac{\partial^2 h_l}{\partial z^2} \quad (13)$$

where the first and the last terms in the right hand side of Eqn. 13 are the gravitational and surface tension effects, respectively.

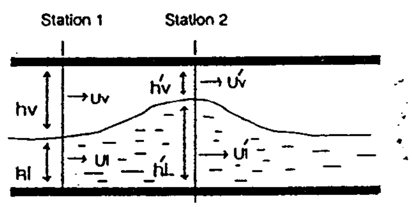

Figure 3 : Formation of Intermittent Flow

Using Bernoulli equation, the energy balance between point 1 and point 2 may be written as

$$P_{ij} + \frac{1}{2}\beta\rho_j g h_j + \frac{1}{2}\rho_j U_j^2 = P_{ij}' + \frac{1}{2}\beta\rho_j g h_j' + \frac{1}{2}\rho_j U_j'^2 \quad (14)$$

where $j=l$ and $\beta=1$ for liquid phase, and $j=v$ and $\beta=-1$ for vapour phase. In above equation P_{ij} equals to P_i.

Assuming that the mass transfer takes place at the interface, the continuity equation for the liquid and vapour phase can be written as

$$\rho_j A_j' U_j' = \rho_j A_j U_j + \beta \dot{m} \Delta z \quad (15)$$

where $\beta = 1$ is for vapour phase and $\beta = -1$ is for liquid phase. In above equation, Δz equals the half length of the curvature, $k^2(h_l' - h_l)A/2$.

Using Eqns. 13 to 15, and the relationship $h_v + h_l = h_v' + h_l'$, and assuming that for small finite disturbances, A_v' and h_v' can be expanded about A_v and h_v, respectively in Taylor series ignoring higher order terms, we obtain the following relation,

$$U_v^2 \ge C^2 \left[\frac{(F_g + F_m)A_v}{(C+1)dA_l/dh_l} + U_l^2\right] \quad (16)$$

where

$$F_g = \frac{4(\rho_l - \rho_v)^2 g}{\rho_v \rho_l} \quad (17)$$

and

$$F_m = \dot{m}\left(\frac{C^2 U_l}{\rho_l A_l} + \frac{C^{-2} U_v}{\rho_v A_v}\right)\frac{g(\rho_l - \rho_v)A}{\sigma} \quad (18)$$

Following Taitel and Dukler[7], C is assumed equal to $(1 - h_l/D)$.

(c) Transition from intermittent to annular flow

For transition from intermittent to annular flow, the model proposed by Taitel and Dukler[6] is used. According to this model, the transition occurs if the value of h_l/D is greater than 0.5.

(d) Transition from intermittent to bubbly flow

The transition from intermittent to bubble flow is derived based on the vertical force balance. The transition is assumed to occur when the bubble turbulent force, F_T, is greater than the bubble buoyancy force, F_B and the force due to mass transfer, F_m.

The effect of mass transfer and heat transfer on the bubble will change the radius of the bubble, the mass contained in the bubble and pressure difference between the bubble and the liquid. The change of mass will change of density of the bubble. The bubble mass change is assumed to be due to the condensation of the vapor inside the bubble on to the bulk liquid or evaporation from the liquid phase to vapor bubble. The latter occurs when the liquid surrounding the bubble is at a superheated condition corresponding to the system pressure. The added or reduced mass will vary with time according to the following equation

$$\Delta m_a = \int_0^{t_c} \frac{H_{lv}(T_l - T_v)S_i}{i_{lv}} dt \quad (19)$$

where t_c is the transport time which equals the bubble growth time.

In this analysis, it is assumed that the bubble radius does not change. Therefore, the force of buoyancy per unit length of the vapour bubble may be written as $F_B = g(\rho_l - \rho_v')A_v$ where ρ_v' equals to $\rho_v + \Delta m_a/A_v$, and the force due to mass transfer per unit length may be written as

$$F_m = [(\rho_l - \rho_v')/\rho_l \rho_v'](\dot{m}/S_i)^2 S_i \quad (20)$$

The force due to turbulence acting is estimated to be $F_T = 1/4\, S_i \rho_l f_l U_l^2$. The final form of the transition criterion is

$$U_l^2 \ge \frac{4g[(\rho_l - \rho_v')A_v + F_m]}{f_l \rho_l S_i} \quad (21)$$

NUMERICAL RESULTS

The first step in the numerical procedure is to calculate the geometrical parameters of the pipe with 37 rod bundles. Typical calculation obtained by Osamusali and Chang[1] is shown in Fig. 4. It is seen that the interfacial area becomes nonmonotonic in the case of bundle geometries.

The second step is to calculate the flow regime transition boundary by solving the simplified mixture momentum equation (Eqn. 5) together with Eqns.12, 16 and 21.

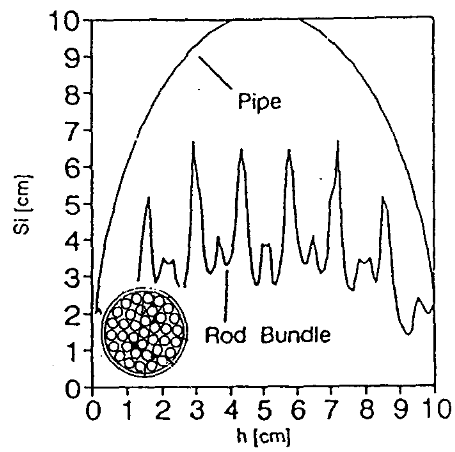

Figure 4: Interfacial Length for 37-Rod Bundle.

Figure 5 shows the comparison between the flow regime map with and without a bundle. This figure shows that many of the transition boundaries are influenced by the existence of bundles in the flow channel.

Figure 6 shows the transition boundaries for intermittent-to-bubble flow. For superheated liquid, it is seen that the transition boundary shifts to lower superficial liquid velocity for high mass transfer, i.e. the transport time (t_c) greater than zero. For subcooled liquid, the transition boundary is shifted to a higher superficial liquid velocity for t_c greater than zero.

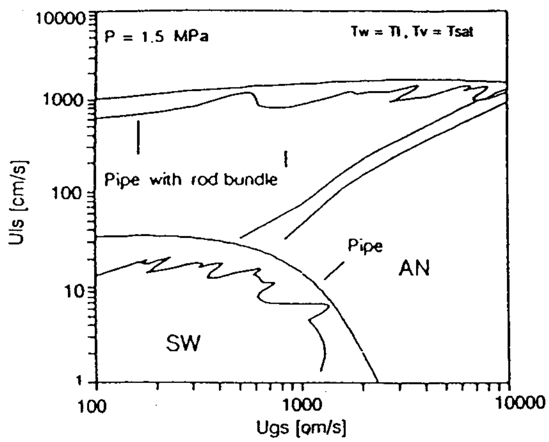

Figure 5 : The Flow Regime Transitions for a Horizontal Pipe with and without Nuclear Bundles

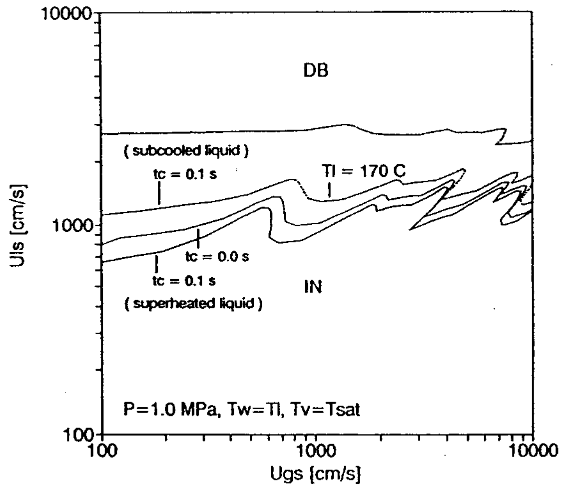

Figure 6: Transition from Intermittent to Bubble Flow

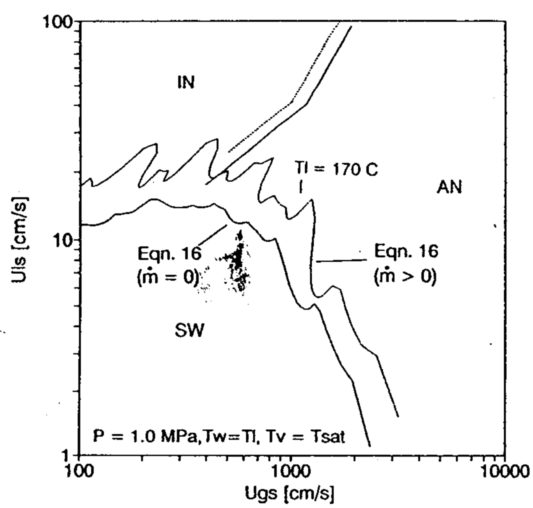

Figure 7 : Transition boundary from Stratified to Intermittent Flow and Intermittent to Annular Flow.

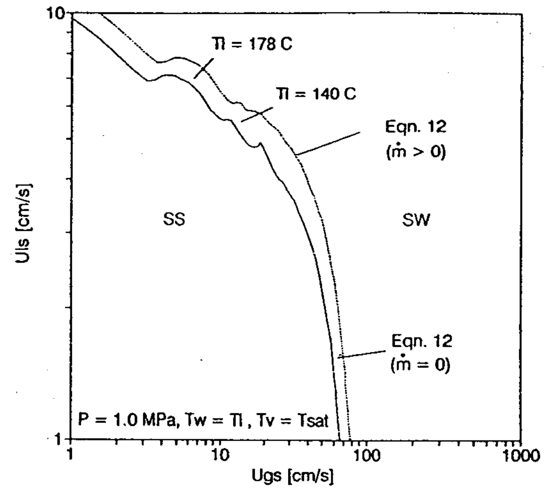

Figure 8 : Transition from Stratified Smooth to wavy Flow.

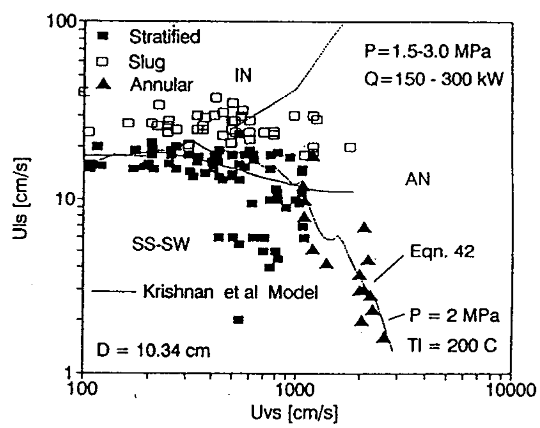

Figure 9 : The Flow Regime Transitions and comparison between the present model and experimental data of Sawamura et al [11].

Figure 7 shows the transition from Stratified Flow to Intermittent Flow, especially for condensing flow. Figure 7 shows that the transition shifts to higher superfical liquid velocity. The reason for this is given below. As the condensation mass transfer takes place at the interface, the liquid level increases.

Figure 8 shows the transition boundary from stratified smooth to wavy flow in the presence and absence of the mass transfer. Mass transfer shows small effect on the formation of the wave growth.

Figure 9 shows the comparison between the present flow regime map and the experimental steam-water two-phase flow data of Sawamura et al [11] obtained for system pressures from 1.5 to 3.0 MPa. Comparison with the model of Krishnan et al. [5] is also shown in Fig. 9.

Transition boundary between intermittent to annular flow is observed to occur at lower superficial vapour velocity than the experimental data of Sawamura et al[11] . Transition boundary between stratified to intermittent is slightly under predicted especially for high vapour flow rates.

CONCLUDING REMARKS

Theoretical investigations have been carried out to predict the flow pattern transitions for steam-water in a horizontal pipe with bundles. The results can be summarized as follows,

1. The transition from intermittent to bubble flow is significantly influenced by the presence of mass transfer.
2. No significant condensing mass transfer effect is observed for the formation of the surface wave under stratified flow conditions.

NOMENCLATURE

A,D	= pipe area, inner pipe diameter
A_l,A_v	= liquid,vapour phase flow area
g	= acceleration due to gravity
h_v,h_l	= vapour, liquid height
i_{lv}	= latent heat of evaporation
m	= rate of mass transfer
P_{il},P_{iv}	= interface-liquid, interface-vapour pressure
Q_l'',Q_v''	= liquid, vapour volumetric heat generation
s	= sheltering coefficient
S_l,S_v,S_i	= liquid,vapour and interfacial perimeter
T_l,T_v,T_w	= liquid, vapour, wall temperature
U_{ls}, U_{vs}	= superficial phase velocities
ϵ	= absolute pipe roughness
μ,ν	= dynamics and kinematics viscosity
τ	= shear stress
σ	= surface tension
ρ	= density

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