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Boiling Crisis in the Horizontal Channel*

(4th Report, Analysis on Burnout Heat Flux in Annular Mist Flow)

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High flow rate prevents gravitational flow stratification even in horizontal tubes and the flow pattern is almost always the annular mist flow.

This paper describes a general theoretical analysis of burnout phenomena in this type of flow.

The effects of the entrainment due to hydrodynamic instability of the liquid sheet and the diffusion of the droplets in the core flow were theoretically analyzed to reveal the mechanism governing the film and droplets flow rate.

This mechanism was confirmed by experiments without heat addition. Then the results were applied to the heated annular mist flow to reveal the properties of burnout.

Experimental data by several authors for a wide range of parameters such as tube diameter, flow rate or pressure were in good agreement with theoretical predictions.

1. Introduction

It has been pointed out⁽²⁾⁽³⁾ that, for low flow rate, the top of the horizontal tube is more liable to dryout or burnout than the bottom due to flow stratification: and, for high flow rate, burnout occurs at the exit of the heated section and the difference between the top and the bottom of the horizontal tube disappears. In the latter case, the burnout phenomena in the horizontal tube must be the same as those of the vertical tube since stratification is not observed. This paper describes an analytical study on the burnout heat flux under such conditions.

It was visually observed⁽¹⁾ that, when the quality was above nearly 0.1, a very thin liquid film with ripples flowed along the wall and high speed steam with liquid droplets flowed in the core region. Thus the flow pattern was the annular mist flow which is the most ordinary type among two-phase flow patterns.

Burnout in the annular mist flow is discussed in this paper.

Observations⁽¹⁾ of the wall temperature, heat flux and the liquid film behavior along the wall near burnout point revealed that burnout in the annular mist flow was the result of extinction of the liquid film accompanied by reduction of the heat transfer coefficient.

Observations of the behavior of fluid flow and burnout heat flux were also made and analyzed by Isbin et al.⁽⁴⁾, Tippets⁽⁵⁾, Becker et al.⁽⁶⁾, Grace⁽⁷⁾, Agafonova⁽⁸⁾.

The liquid film along the wall loses its mass by evaporation and entrainment, and regains the entrained droplets by diffusion from the core. The difference between the loss and the regain is the net decrease in the film flow rate whose vanishing point is identical to the burnout point. Theoretical prediction of the loss and the regain is therefore essential in theoretical analysis of burnout. Theoretical studies in the past on the diffusion and entrainment mostly assume some empirical relations whose empirical constants must be obtained from experimentally determined burnout heat flux.

In this paper, a two-phase flow without heating is analyzed first to find functional relations on the entrainment and the diffusion. The relations are confirmed by experiment and are then applied to theoretical burnout analysis.

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Predicted burnout heat flux by this theoretical analysis is in agreement with experiment for a wide range of flow rates, pressures and tube diameters.

Nomenclature

- a : average liquid film thickness
 a^+ : dimensionless liquid film thickness
 A, B, C : constants
 C_c : concentration of liquid droplets
 D : tube diameter
 D_p, D_l : quantities defined by Eqs. (31) and (32) respectively
 E_c, E_d, E_e and E_v : quantities given by Eqs. (35), (27), (21) and (34), respectively
 $E_{qe} = E_v + E_c$
 G, G_l, G_{lf}, G_{lc} and G_g : total flow rate, liquid flow rate, liquid film flow rate, droplets flow rate and gas flow rate
 h and $h_{\max}$: height and maximum height of the wave crest
 K_c, K_e, K_d, K_{ed} and K_p : constants
 k : wave number
 L_h and L_s : heated length and effective heated length
 l_1, l_2 : mixing length
 n : quantity contained in time fact or $\exp(nt)$
 p : pressure
 q : heat flux
 r : latent heat of evaporation
 $R_{eg} = \frac{DU_g}{\nu_g}$
 u^+ and v^+ : dimensionless velocities.
 $u/\sqrt{\tau_w/\rho}$ and $v/\sqrt{\tau_w/\rho}$
 U_g : gas velocity
 U_{rel} : effective relative velocity
 v' : component of turbulence in y direction
 x : quality
 y^+ : dimensionless distance
 z : distance in the flow direction
 α : real part of n
 γ : specific weight
 η : displacement
 η_0 : constant
 λ : wave length
 λ_g : friction coefficient when gas flowed filling the total cross section
 μ : viscosity
 ν : kinematic viscosity
 ρ : specific mass
 σ : surface tension
 τ_w : shearing stress on the wall
 ϕ : velocity potential
 ϕ_g : Martinelli's parameter

Suffix

- l : liquid
 g : gas
 c : core flow containing liquid droplets
 BO : burnout

2. Liquid film flow rate and droplets flow rate in the adiabatic two phase annular mist flow

In a fully developed adiabatic annular mist flow, both the liquid flow rate and the droplets flow rate must be constant along the stream. On the other hand, it is known⁽⁹⁾ that liquid droplets in the core continuously disperse and supply liquid to the liquid film along the wall. Since the liquid film flow rate is constant along the stream, some liquid must be continuously released from the liquid film into the gas core, that is, the liquid film must be hydrodynamically unstable and continuously exchange liquid droplets with the gas core.

The rate of liquid release from the film is dependent on the hydrodynamic instability of liquid film, and the rate of droplet diffusion from the gas core is dependent on the turbulence in the gas core. In the following, these relations are analyzed to obtain the film flow rate which is compared with experiments.

2.1 Liquid film instability

The coordinate system in the following discussion on the instability of the gas-liquid interface is as indicated in Fig. 1. The core gas containing liquid droplets flows with an effective velocity U_{rel} relative to the liquid film. The coordinate system is fixed on the moving liquid film. The effect of the tube curvature is neglected because the film is thin. Flow velocity is considered to be so high as to make the gravity effect negligible. Viscosity is also neglected for the sake of simplicity in this section (2.1) in discussing the hydrodynamic instability.

Velocity potential in the liquid film or gas core is denoted by ϕ_l or ϕ_c , respectively. Suffix l or c is omitted when the distinction is

Fig. 1 Coordinate system

unnecessary.

Equations of continuity and motion yield

$$\frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial y^2} = 0 \quad \dots\dots\dots (1)$$

$$\frac{p}{\rho} = \frac{\partial \phi}{\partial t} - \frac{1}{2}(u^2 + v^2) + C \quad \dots\dots\dots (2)$$

Boundary conditions are

$$\text{at } y=0, \quad -\frac{\partial \phi_l}{\partial y} = 0 \quad \dots\dots\dots (3)$$

$$\text{at } y=\infty, \quad \phi_c = -U_{rel}x \quad \dots\dots\dots (4)$$

$$\text{at } y=a, \quad -\frac{\partial \phi_c}{\partial y} = \frac{\partial \eta}{\partial t} + U_{rel} \frac{\partial \eta}{\partial x} \quad \dots\dots\dots (5)$$

$$\text{at } y=a, \quad \frac{\partial \eta}{\partial t} = -\frac{\partial \phi_l}{\partial y} \quad \dots\dots\dots (6)$$

$$\text{at } y=a, \quad p_c - p_l = \sigma \frac{\partial^2 \eta}{\partial x^2} \quad \dots\dots\dots (7)$$

Let the time factor be $\exp(nt)$ and the space factor be $\exp(ikx)$. The elementary solutions of Eq. (1) satisfying Eqs. (3) and (4) are

$$\phi_l = A \cosh(ky) \exp(ikx + nt) \quad \dots\dots\dots (8)$$

$$\phi_c = B \exp(-ky) \exp(ikx + nt) - U_{rel}x \quad \dots\dots\dots (9)$$

From Eqs. (6) and (8) the displacement η is given by the following equation:

$$\eta = -\frac{kA}{n} \sinh(ka) \exp(ikx + nt) \quad \dots\dots\dots (10)$$

Assuming small displacement of the 1st order, and using Eqs. (2), (5), (7), (8), (9) and, (10) we get

$$(n + U_{rel}ki)^2 \rho_c + \rho_l n^2 \coth ka = -\sigma k^3 \quad \dots\dots\dots (11)$$

Let α be the real part of n . Then Eq. (11) yields

$$\alpha^2 = \frac{\rho_c}{\rho_l} U_{rel}^2 k^2 - \frac{\sigma}{\rho_l} k^3 \quad \dots\dots\dots (12)$$

by assuming that $\rho_c \ll \rho_l$ and $1 \leq \lambda/a \leq 5^{(5)}$.

Equation (12) indicates that α depends on wave number k ($=2\pi/\lambda$) or wave length. If α is positive, the wave is unstable, that is, the crest of the wave grows infinitely.

Waves of various wave lengths coexist on actual interface. Let us, however, assume that the most rapidly growing wave whose α is the maximum prevails dominantly all over the interface.

The maximum α and the corresponding wave length, which are denoted by α_c and λ_c , respectively, are as follows:

$$\alpha_c = \frac{2}{3\sqrt{3}} \sqrt{\frac{\rho_c}{\rho_l}} \frac{\rho_c}{\sigma} U_{rel}^3 \quad \dots\dots\dots (13)$$

$$\lambda_c = \frac{3\pi\sigma}{\rho_c U_{rel}^2} \quad \dots\dots\dots (14)$$

In deriving these results, the flow is assumed to be a potential flow. Actually the velocity distribution is not uniform and the relative velocity between liquid film and gas is difficult to define. Therefore, the velocity difference at

the points equally apart from the interface by a distance l_1 is assumed to give an effective relative velocity U_{rel} , that is,

$$U_{rel} = l_1 \left(\frac{du_g}{dy} \right)_{y=a} + l_1 \left(\frac{du_l}{dy} \right)_{y=a} \quad \dots\dots\dots (15)$$

The distance l_1 measured from the interface is an effective thickness of a layer which has influence on the interface. Therefore, l_1 is similar to the mixing length in the turbulent flow theory. Following the relation of Prandtl's mixing length l_2 ($=k_2 y$), l_1 is assumed to be equal to $k_1 y$. Then, by using Eq. (15) after the method by Tippetts⁽⁵⁾, we get

$$U_{rel} = \frac{k_1}{k_2} \sqrt{\frac{\tau_w}{\rho_c}} \left(1 + \sqrt{\frac{\rho_c}{\rho_l}} \right) = \frac{k_1}{k_2} \sqrt{\frac{\tau_w}{\rho_c}} \quad \dots\dots\dots (16)$$

The wall shear stress τ_w in Eq. (16) is obtained from the pressure drop which in turn is dependent on the Martinelli's⁽¹⁰⁾ parameter Φ_g . Thus we get finally

$$U_{rel} = \frac{k_1}{k_2} \sqrt{\frac{\lambda_g}{8} \frac{\rho_g}{\rho_c}} \Phi_g U_g \quad \dots\dots\dots (17)$$

This equation indicates that the effective relative velocity U_{rel} is proportional to the average core gas speed U_g .

2.2 Rate of droplets generation from the liquid film by interface instability

If the crest of the unstable wave whose α in Eq. (12) is positive grows to a limiting height h_{max} , the crest will be blown off by the core gas, producing liquid droplets. It is assumed that the most rapidly growing wave prevails dominantly and the rate of droplets generation from the liquid film is proportional to the growing velocity of the crest when being blown off.

Then, E_s , the rate of droplets released from the unit area of the film per unit time, is given by,

$$E_s \propto \frac{\lambda_c}{2} \left(\frac{dh}{dt} \right)_{h=h_{max}} \gamma_l \frac{1}{\lambda_c} \quad \dots\dots\dots (18)$$

Considering that Eq. (10) indicates the height h of the wave as $h = \eta_0 \exp(\alpha_c t)$,

$$E_s \propto \alpha_c h_{max} \gamma_l \quad \dots\dots\dots (19)$$

Maximum height of the crest h_{max} in annular mist flow is known to be appreciably dependent on the average liquid film thickness⁽¹¹⁾. It is therefore assumed in the first approximation that the maximum height h_{max} is proportional to the average liquid film thickness, that is,

$$h_{max} \propto a \quad \dots\dots\dots (20)$$

Substituting Eqs. (13), (17), and (20) into Eq. (19), we get

$$E_s = K_s \frac{\lambda_g}{8} \left(\frac{\mu_l U_g}{\sigma} \right) \gamma_l U_g a^+ \Phi_g^2 \quad \dots\dots\dots (21)$$

where K_s is a constant to be found by experiment, and a^+ is the dimensionless liquid film thickness.

Actual wave configuration may not neces-

sarily be so smooth as to justify the assumption of small displacement, but, in the present state of analysis, Eq. (21) is used as the first approximation in our further analysis.

2.3 Liquid film flow rate

The liquid flow rate G_{lf} in the liquid film per unit area of the channel cross section is given by,

$$G_{lf} = \frac{4}{D} \int_0^a \gamma_l u_l dy = \frac{4}{D} \gamma_l \nu_l F(a^+) \quad \dots\dots\dots (22)$$

where,

$$F(a^+) = \int_0^{a^+} u^+ dy^+ \quad \dots\dots\dots (23)$$

Considering that the flow velocity distribution in the liquid film must be similar to the velocity distribution near the wall in the single phase flow, we may make use of the following well known relations for the velocity distribution⁽¹²⁾:

$$\left. \begin{aligned} \text{at } y^+ \leq 5, \quad u^+ &= y^+ \\ \text{at } 5 \leq y^+ \leq 30, \quad u^+ &= -3.05 + 5.00 \ln y^+ \\ \text{at } 30 \leq y^+, \quad u^+ &= 5.5 + 2.5 \ln y^+ \end{aligned} \right\} \quad \dots\dots\dots (24)$$

When the dimensionless liquid film thickness a^+ is known, the liquid flow rate in the liquid film, G_{lf} , can be calculated by Eqs. (22), (23) and (24).

2.4 Droplets diffusion in the core flow

The droplets in the gas core get radial velocity components from the turbulence around them and have chances to move toward the wall. If the droplets come to a very close distance from the wall, the turbulence dies out and the inertia of the droplets makes them collide with the wall to supply liquid to the liquid film.

Assuming that the diffusion rate of droplets to the wall is proportional to the radial velocity component v' of the turbulence and the droplets concentration C_c in the core, we get

$$E_d \propto v' C_c \quad \dots\dots\dots (25)$$

According to Hinze⁽¹³⁾, turbulent radial velocity component v' in the single phase flow is nearly equal to the friction velocity v^+ . Assuming that the flow conditions in the core of the two phase annular mist flow are similar to the single phase gas flow, we get

$$v' \doteq v^+ = \sqrt{\tau_w / \rho_c} = \sqrt{\frac{\rho_g}{\rho_c} \frac{\lambda_g}{8} \phi_g U_g} \quad \dots\dots\dots (26)$$

Substituting Eq. (26) into Eq. (25), we get

$$E_d = K_d \sqrt{\frac{\rho_g}{\rho_c} \frac{\lambda_g}{8} \phi_g U_g} C_c \quad \dots\dots\dots (27)$$

where K_d is a proportional constant.

2.5 Comparison of computed flow rates with experiments

When the gas flow rate, the total liquid flow

rate, properties of the fluids and the channel dimensions are known, both the droplets flow rate and liquid film flow rate can be analytically calculated by using the relations derived above.

For the fully developed flow, droplets and liquid film flow rate do not change along the flow direction, that is, the rate of droplets generation from the liquid film and the droplets diffusion to the liquid film must be equal.

Equating E_s and E_d in Eqs. (21) and (27), we get

$$G_{lc} = U_g C_c = K_{cd} \left(\frac{\mu_l U_g}{\sigma} \right) \sqrt{\frac{\lambda_g}{8} \frac{\rho_c}{\rho_g}} \gamma_g U_g \phi_g a^+ \quad \dots\dots\dots (28)$$

where G_{lc} = the droplets flow rate,

$$K_{cd} = K_c / K_d \quad \dots\dots\dots (29)$$

Denote total liquid flow rate by G_l , i.e.,

$$G_l = G_{lc} + G_{lf} \quad \dots\dots\dots (30)$$

Unknown quantities G_{lc} , G_{lf} and a^+ are obtained from Eqs. (22), (28) and (30).

In the following calculation, the empirical constant K_{cd} in Eq. (28) was taken as 0.38 to give the best result.

Results of calculation are compared with those of experiments in Figs. 2, 3, and 4.

Comparative experimental studies were all made on air-water two phase flow at the

Fig. 2 Comparison with Collier's⁽¹⁴⁾ experiments

Fig. 3 Comparison with Magiros's⁽¹⁵⁾ experiments

atmospheric pressure. No experiment under variable fluid properties was available. However, the experiments cover a wide range of tube diameters and flow rates.

Experimental results might be influenced by particular experimental equipments such as the air-water mixing equipment, the calming section and the measuring apparatus. Scattering of the points in Figs. 2, 3 and 4 may be partly due to these unavoidable experimental particularities. Since the analytical theory explained above contains only one empirical constant (i.e., K_{ed} , which was taken as 0.38) and the deviations from a wide range of experimental results are as indicated in these diagrams, the theory is believed to be satisfactorily proved.

2.6 Determination of the rates of droplets generation and droplets diffusion

The rates of droplets generation from the liquid film and droplets diffusion from the gas core are given by Eqs. (21) and (27) respectively

Sign	D mm	U_g m/sec	Worker
○ ⊙ ⊖	26.0	25 50 75	Wicks et al. (16)
△ △ △ △	26.0	25 50 75 100	Magiros et al. (15)
▽ ▽ ▽ ▼	31.8	21 36 56 69	Collier et al. (14)
× + * ※	74.8	5.9 8.0 9.3 11.0	Wicks et al. (16)

Fig. 4 Comparison with experiments

where K_e and K_d must be determined empirically.

Paleev et al.⁽⁹⁾ suggested the following empirical relation as a result of his experiment on air-water two phase flow.

$$E_d = D_p(U_g C_c), \quad D_p = \frac{K_p}{Re_g^{0.25}} \quad (31)$$

where K_p is slightly dependent on the density of droplets in the core and lies between 0.02 and 0.03.

Let us rewrite Eq. (27) for the purpose of comparing with Eq. (31) in the following form:

$$E_d = D_t(U_g C_c), \quad D_t = K_d \sqrt{\frac{\rho_g}{\rho_c} \frac{\lambda_g}{8} \phi_g} \quad (32)$$

D_p and D_t in Eqs. (31) and (32) are compared in Fig. 5 where $K_d = 0.022$ is used and ρ_c is the average mass density of the gas core containing droplets. In calculating ρ_c , the relative velocity between core gas and droplets was neglected.

Very little experimental data are available on the droplets diffusion in two phase annular mist flow. It may be appropriate to evaluate K_d as 0.022 according to Paleev's experimental results as shown in Fig. 5.

K_e in Eq. (21) cannot be determined directly because no experimental study has yet been made on droplets generation from unstable liquid films. However, in Section 2.5 of this paper it was proved that by assuming $K_{ed} = K_e/K_d = 0.38$ good correlations were obtained in many experimental results. Making use of $K_d = 0.022$, we get $K_e = 0.0084$.

Thus, E_e and E_d in Eqs. (21) and (27) are numerically obtainable for any experimental conditions so far as the annular mist flow is concerned.

3. Burnout heat flux

3.1 Fundamental equations

Consider an annular mist flow flowing in the circular tube uniformly heated circumferentially but not necessarily uniformly heated in the flow direction.

Factors which decrease the liquid film flow rate are as follows:

Fig. 5 Comparison of D_p with D_t

- (1) evaporation rate due to heating E_v ;
- (2) rate of droplets released from liquid film due to its instability, E_e ;
- (3) rate of droplets entrained by evaporating steam flow, E_c .

Meanwhile, the factor which supplies liquid to the liquid film is droplets diffusion, E_d .

Then, G_{lf} , the liquid film flow rate, is found by the mass balance in the small interval dz as follows:

$$\frac{\pi D^2}{4} \frac{dG_{lf}}{dz} = -(E_v + E_c + E_e - E_d) \pi D \quad (33)$$

The evaporation rate E_v is as follows:

$$E_v = q/r \quad (34)$$

Rate of droplets entrained by evaporating steam flow may reasonably be assumed proportional to $q/r\gamma_g$ (the average steam velocity generated by evaporation), and to the droplets concentration C_c , that is,

$$E_c = K_c \frac{q}{r} \frac{C_c}{\gamma_g} \quad (35)$$

where K_c must be between 0 and 1 according to the relative velocity between droplets and evaporating steam. For the present, $K_c=0.5$ is adopted for the sake of simplicity.

Rate of droplets generation E_e due to liquid film instability and diffusion rate of droplets E_d are considered to be calculated under the local condition in the heated flow by using Eqs. (21) and (27). Heated flow does not get fully developed and E_e and E_d do not balance, as was the case in the fully developed adiabatic flow.

Now, considering the mass balance of the total liquid flow G_l in the interval dz , we get

$$\frac{\pi D^2}{4} \frac{dG_l}{dz} = -\pi D \frac{q}{r} \quad (36)$$

Equations (33) and (36) are the fundamental equations by which liquid film flow rate G_{lf} in the flow direction can be calculated by iterating integration starting from an initial value of G_{lf} . Burnout point can be definitely found as the point where G_{lf} reaches zero.

3.2 Calculating procedure

The right hand side of Eq. (33) must be rewritten in terms of z and G_{lf} in integrating Eq. (33).

In the following discussion, the heat flux is assumed uniform in the flow direction. This assumption is not a necessary condition in carrying out the calculation.

Now, let the total liquid flow rate be G_{l0} at $z=0$. Then the total liquid flow rate G_l at $z=z$ is as follows:

$$G_l = G_{l0} - \frac{q}{r} \frac{4z}{D} \quad (37)$$

The gas velocity U_g at z is as follows:

$$U_g = \frac{q}{r} \frac{1}{\gamma_g} \frac{4z}{D} + U_0 \quad (38)$$

where U_0 is the gas flow velocity at $z=0$.

C_c and ρ_c are given by the following relations, respectively.

$$C_c = \frac{G_l - G_{lf}}{U_g}, \quad \rho_c = \rho_g \left(1 + \frac{G_l - G_{lf}}{G_g}\right) \quad (39)$$

Using Eqs. (37), (38), (39) and (22), the right hand side of Eq. (33) can be written in terms of z and G_{lf} .

Integrating Eq. (33) by Runge-Kutta method for given tube diameter D , flow rate G_{l0} , heat flux q and pressure (fluid properties), we get the liquid film flow rate G_{lf} in relation to the

$q=10^6 \text{ kcal/m}^2 \text{ hr}$, $L_s=2.52 \text{ m}$, $D=5.2 \text{ mm}$,
 $p=70 \text{ ata}$, $G=7.82 \times 10^6 \text{ kg/m}^2 \text{ hr}$

Fig. 6 Calculation of various quantities

heated length z . Thus the heated length from the inlet to the burnout point where $G_{lf}=0$ is found and also the burnout quality are obtained.

3.3 Examples of results of analytical computations

The domain of integration of Eq. (33) must be limited to the annular mist flow region. As is well known in the adiabatic two phase flow⁽¹⁷⁾, annular or annular mist flow dominates a wide quality region excluding only the very small quality region. For the heated flow, the transition point to the annular flow shifts to a still smaller quality point⁽¹⁸⁾ at which the total liquid flow rate is very closely equal to the liquid film flow rate. Experimental data on the critical steam velocity U_0 at the transition point are rather scarce. It is reasonable to estimate U_0 as a small positive quantity. In this paper U_0 is tentatively assumed to be 0.5 m/sec.

Solid lines in Figs. 6~8 indicate the behavior of quantities such as G_{lf} , E_e , E_d etc. analytically computed by using Eqs. (33)~(39) for various pressures and flow rates. Behavior of corresponding adiabatic fully developed flow is also given by the chain lines.

$q=10^6 \text{ kcal/m}^2 \text{ hr}$, $L_s=0.75 \text{ m}$, $D=5.2 \text{ mm}$
 $p=70 \text{ ata}$, $G=2 \times 10^6 \text{ kg/m}^2 \text{ hr}$

Fig. 7 Calculation of various quantities

Following are to be pointed out.

(1) As the quality increases, the liquid film flow rate decreases and finally reaches zero at a quality less than unity. The point of zero film flow is the burnout point.

(2) E_e approaches zero near the burnout point. This fact indicates that a thin liquid film hardly releases droplets due to its instability.

(3) For large flow rate as in Fig. 6, E_e , E_d or E_c becomes much larger as compared with E_v and the liquid film flow rate G_{lf} decreases rapidly mainly due to the large quantity of E_e . But for smaller flow rate as in Fig. 7 E_e , E_d or E_c becomes small as compared with E_v and decrease of G_{lf} is not so rapid. Above results explain the experimental fact that the burnout quality for small flow rate is larger than that for large flow rate.

(4) Lower pressure results in higher amounts of $E_c (=F_{qc} - E_v)$, E_d and E_e as shown in Figs. 7 and 8. This is mainly due to the reduction of steam density and the corresponding increase in the flow velocity.

$q=10^6 \text{ kcal/m}^2 \text{ hr}$, $L_s=0.81 \text{ m}$, $D=5.2 \text{ mm}$
 $p=4 \text{ ata}$, $G=2 \times 10^6 \text{ kg/m}^2 \text{ hr}$

Fig. 8 Calculation of various quantities

3.4 Comparison of calculated and experimental burnout heat flux

As mentioned before, if the tube diameter D , the flow rate G , the heat flux q and the pressure p are given, then the burnout quality x_{BO} and the heated length from the zero quality point to the burnout point (hereafter referred to as the effective heated length and denoted by L_s) can be calculated. In other words, for a set of any given amounts of D , G and p , corresponding x_{BO} and L_s can be obtained for various heat fluxes, that is, the following relations can be found:

$$q_{BO} = q_{BO}(x_{BO}), \quad D, G, p = \text{const.} \quad (40)$$

$$q_{BO} = q_{BO}(L_s), \quad D, G, p = \text{const.} \quad (41)$$

Examples of L_s versus q_{BO} curves are shown in Figs. 9 and 10 from which q_{BO} is found for given L_s , which in turn is obtained from the heat balance as follows:

$$L_s = \frac{D}{4} \frac{r x_{BO}}{q_{BO}} G \quad (42)$$

In evaluating L_s from Eq. (42) for the flow which is subcooled at the inlet, the subcooled region must be excluded from L_s , which has to be measured starting from the zero quality

Fig. 9 Relation between effective heated length and burnout heat flux

Fig. 10 Relation between effective heated length and burnout heat flux

point. If the flow has a positive quality at the inlet, G_{if} along the flow must be calculated by integrating the primary Eq. (33) for a given G_{if}

Fig. 11 Comparison with Ishigai's⁽³⁾ experiments

Fig. 12 Comparison with Bertolotti's⁽¹⁹⁾ experiments

Fig. 13 Comparison with Silvestri's⁽²⁰⁾ experiments

at the inlet. Ordinarily, however, G_{if} at the inlet is rather difficult to evaluate. In this connection it should be reminded that burnout is the result of the cumulative effect along the heated section. Thus it may not make much difference if L_s by Eq. (42) (which is somewhat imaginative as in this case) is used in finding the burnout heat flux. The only condition in this case is that the heated length is not extremely short.

Comparisons of calculated and experimented results are given in Figs. 11, 12 and 13. These diagrams indicate that the analytically calculated q_{Bo} agree fairly well with experimental data for a wide range of tube diameters, flow rates and pressures.

4. Conclusion

The effects of the entrainment due to hydrodynamic instability of the liquid film and the diffusion of the droplets in the gas core were analytically accounted for in examining the heated annular mist flow.

The result was confirmed by experiments without heat addition. Then the result was applied to the heated annular mist flow. The burnout point was evaluated as the point at which the liquid film vanished.

Experimental data by several authors for a wide range of parameters were in good agreement with computed results by the analytical theory developed in this paper.

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