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A Mechanistic Dryout Prediction in the Uniformly Heated Vertical Tube for the Saturated Upward Flow

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Abstract

A Mechanistic dryout prediction model without any empirical constant is proposed for vertical tube geometry that covering the wide critical heat flux experimental ranges. The assumption of the initial film thickness is removed by phenomenological calculation of the void fraction at the onset of annular flow location using the churn-to-annular flow criterion of the flow pattern map. The annular flow starting point in the tube channel obtained through the profile-fit model and the energy balance in the heated section after obtained the flow quality form the flow quailty and superficial velocity relationship. This approach improved the prediction accuracy and extended the applicable range of the experimental data. It is tested by worldwide water data covering the wide parametric ranges, length-to-diameter ratio of 26~1025, channel exit quality over 10%, flow rate of 180 ~7000 kg $/m^2-s$ and system pressure of 0.5 ~16 MPa. The total of 3026 data was calculated with the mean of 0.98 and root mean square error of 11% and the model shows nearly complete convergence characteristics.

I. Introduction

The dryout, a mechanism of the critical heat flux (CHF) in the annular flow pattern, can be described that if the liquid film formed on the wall, it goes through deposition of the liquid droplet from the core, liquid entrainment to the core and evaporation by the wall heat flux. The liquid film thickness decreases as the heat flux increases. When the heat flux is high enough to dryout this liquid film, it causes an abrupt rise of temperature at the dryout location that leading to melting of the heater. After Whally proposed a Liquid Film Dryout (LFD) model for tube channel, it is developed continually by many investigators as improving constitutive relations[1-4], and extended annulus and bundle geometry[5-8]. But their models have an empirical constant for the void fraction or quality at the onset of annular flow location. Whalley assumed 1% of the quality at the onset of annular flow location to calculate the initial film thickness of the annular flow[1]. Levy suggested 80% of the void fraction at the onset of annular flow location [2]. Katto reduced 60% after introduced the critical film thickness concept that there is no entrainment if the liquid film on the wall less than critical film thickness [3]. Physically, the void fraction at the onset of annular flow location is not a constant. It can be extracted from flow pattern map. Taitel et. al.'s [9] expressed the superficial velocity at the annular flow starting point as a function of surface tension and thermodynamic properties as,

$$j_g = 3.1\left[\frac{\sigma g(\rho_f - \rho_g)}{\rho_g{}^2}\right]^{1/4} \quad (1)$$

The constant 3.1 is less than the Kutateladze number 3.2, which is the flow reversal criterion in a vertical tube suggested by Pushkina-Sorokin[10]. Because of the flow quality can be obtained by flow quailty and superficial velocity relationship as $x_{an} = \frac{j_g \rho_g}{G}$, the void fraction at the onset of annular flow can be calculated by the following void-quality relationship,

$$\alpha_{an} = \frac{x_{an}}{C_o[x_{an} + \frac{\rho_g}{\rho_f}(1 - x_{an})] + \rho_g \frac{V_{gj}}{G}} \quad (2)$$

where V_{gj}, C_o are the drift velocity and the drift coefficient.

II. Modeling

II-A Governing Equations

The entrainment, deposition, and evaporating process on the liquid film surface are represented in Fig. 1. The governing equation in the liquid film flow is set from the location z = z_{an}, which is the onset of annular flow location.

The mass balance equation in the control volume for the liquid film on the heated wall is

$$\frac{dG_f}{dz} = \frac{4}{d}\left(D - E - \frac{q''}{h_{fg}}\right) \quad (3)$$

where q'' is the heat flux, h_{fg} the latent heat of vaporization, d the tube diameter, G_f the flow rate of the liquid film, D the droplet deposition rates onto the liquid film, and E the droplet entrainment rate from the liquid film to the vapor core.

It is assumed that the entrainment rate becomes zero if the liquid film thickness is less than the critical film thickness, δ_c, given by Katto[3] as

$$d_c = 0.00536\, s\, r_g \left(\frac{r_g}{r_f}\right)^{0.4} \left(\frac{h_{fg}}{q''}\right)^{2} \left(1+\frac{r_g}{r_f}\right) \qquad (4)$$

where s is the surface tension and r_f, r_g are the density of liquid and vapor, respectively.

II-B Constitutive Relations

The deposition rate of droplets from the vapor core on to the liquid film is

$$D = kC \qquad (5)$$

where k is the deposition or mass transfer coefficient (m/s), C the liquid concentration away from the liquid film to the vapor core (kg/m3) .The liquid concentration is written as

$$C = \frac{(G(1-x) - G_{fi} - G_{fo})}{\left\{\dfrac{G\,x}{r_g} + \dfrac{G(1-x) - G_{fi} - G_{fo}}{r_f}\right\}} \qquad (6)$$

Katto[3] suggested a simplified form for the mass transfer coefficient of Whalley[1] as

$$\left.\begin{aligned} k &= 0.405 s^{0.915} \quad for\ s < 0.0383, \\ k &= 9.48\times10^{4} s^{4.70} \quad for\ s > 0.0383. \end{aligned}\right\} \qquad (7)$$

The entrainment rate from the liquid film to the vapor core is given by

$$E = kC_{eq} \qquad (8)$$

where C_{eq}, an equilibrium concentration that would be in equilibrium with the film flow rate under adiabatic conditions (kg/m3). The equilibrium concentration can be expressed in terms of hydrodynamic equilibrium quality such that

$$C_{eq} = \frac{(G(1-x_{eq}) - G_{fi} - G_{fo})}{\left\{\dfrac{G\,x_{eq}}{r_g} + \dfrac{G(1-x_{eq}) - G_{fi} - G_{fo}}{r_f}\right\}}\ . \qquad (9)$$

The hydrodynamic equilibrium quality x_{eq} in the above equation could be obtained by the Levy model[2] as below:

$$\left.\begin{aligned} x_{eq} &= 1 - \frac{G_l / G}{1-\sqrt{1/y}} \quad for\ Y_f^{+} \geq 30, \\ x_{eq} &= 1 - \frac{G_l / G}{1-\sqrt{1/y'}} \quad for\ Y_f^{+} < 30, \end{aligned}\right\} \qquad (10)$$

where the entrainment parameter y is the root of

$$y = 1 + \left[\frac{2}{0.4 x_{eq}^{2}} \frac{s\, r_f}{G^{2} d} \left\{\left(\frac{r_f}{r_g}\right)^{1/y} - 1\right\}\right]^{0.5}$$

and y' is given by

$$y' = 1 + \sqrt{2}(y - 1)\,.$$

The dimensionless film thickness, Y_f^+ , has a triangular relationship with the average film flow rate G_f and wall shear stress τ_w as

$$\frac{G_f/\rho_f}{\sqrt{\tau_w/\rho_f}} = \frac{2}{R^{+2}}K(Y_f^+, R^+) \qquad (11)$$

where

$$K(Y_f^+, R^+) = \tfrac{1}{2}R^+Y_f^{+2} - \tfrac{1}{3}Y_f^{+3}, \qquad for\ Y_f^+ < 5,$$

$$K(Y_f^+, R^+) = 12.51R^+ - 10.45 - 8.05R^+Y_f^+ + 2.775Y_f^{+2} + 5R^+Y_f^+\ln Y_f^+ - 2.5Y_f^+\ln Y_f^+, \qquad for\ 5 < Y_f^+ < 30,$$

$$K(Y_f^+, R^+) = 3R^+Y_f^+ - 63.9R^+ - 2.125Y_f^{+2} - 1.25Y_f^{+2}\ln Y_f^+ + 2.5R^+Y_f^+\ln Y_f^+ + 573.21, \qquad for\ Y_f^+ > 30,$$

with

$$R^+ = \frac{R\rho_f\sqrt{\tau_w/\rho_f}}{\mu_f}, \quad Y^+ = \frac{Y_f\rho_f\sqrt{\tau_w/\rho_f}}{\mu_f},$$

where R is the radius of tube, Y_f the distance perpendicular to the wall or thickness and wall shear stress is calculated as

$$\tau_w = \frac{1}{2}C_{fi}\rho_g\left(\frac{Gx_{eq}}{\rho_g}\right)^2 \qquad (12)$$

where C_{fi} is the interfacial friction factor. Hewitt-Whalley[11] proposed this friction factor as

$$C_{fi} = 0.079\,\mathrm{Re}_g^{-\frac{1}{4}}\left[1 + 24\left(\frac{\rho_f}{\rho_g}\right)^{1/3}\frac{Y_f}{d}\right]$$

II-C Calculation procedure of the initial condition

1) Obtaining the vapor superficial velocity using the equation (1)

2) The flow quality of the onset of annular flow is:

$$x_{an} = \frac{j_g\rho_g}{G}$$

3) Then calculation of void fraction at the onset of annular flow:

$$\alpha_{an} = \frac{x_{an}}{C_o[x_{an} + \frac{\rho_g}{\rho_f}(1 - x_{an})] + \rho_g\frac{V_{gj}}{G}}$$

where V_{gj}, C_o are calculated from Dix model[12]:

$$V_{gj} = 2.9\left[\frac{\sigma g(\rho_f - \rho_g)}{\rho_f^2}\right]^{1/4} \ \& \ C_0 = \beta\left(1 + (1/\beta - 1)^{\alpha}\right)$$

where β and α are defined as:

$$b = \frac{J_g}{J_f + J_g} = \frac{1}{1 + \frac{1-x}{x} \cdot \frac{r_g}{r_f}}$$

$$a = \left(\frac{r_g}{r_f} \right)^{0.1}$$

4) Calculation of enthalpy at the bubble detachment point from Levy[13]:

$$h_l - h_d = \frac{q^{"} C_{pl}}{h} - Q \cdot C_{pl} \cdot \Pr \cdot Y_B^{+} \qquad 0 \le Y_B^{+} \le 5$$

$$h_l - h_d = \frac{q^{"} C_{pl}}{h} - 5Q \cdot C_{pl} \left[\Pr + \ln\left[1 + \Pr\left(\frac{Y_B^{+}}{5} - 1 \right) \right] \right] \qquad 0 \le Y_B^{+} \le 30$$

$$h_l - h_d = \frac{q^{"} C_{pl}}{h} - 5Q \cdot C_{pl} \left[\Pr + \ln(1 + 5\Pr) + 0.5 \ln\left(\frac{Y_B^{+}}{30} \right) \right] \qquad 30 \le Y_B^{+}$$

Where h is the heat transfer coefficient in terms of liquid mixed mean temperature and calculated by:

$$\frac{hD}{k_l} = 0.023 \cdot \mathrm{Re}^{0.8} \Pr^{0.4}$$

k_l is the liquid thermal conductivity. Q is a nondimensional term defined as:

$$Q = \frac{q^{"}}{C_{pl}\left(\sqrt{t_w r_l}\right)}$$

where the wall shear stress t_w is equal to: $t_w = \frac{fG^2}{8 r_l}$ and the friction factor is obtained from

$$f = 0.0055\left\{1 + \left[2 + 10^6 / (GDm_l)\right]^{1/3}\right\}$$

5) We can assume the quality at the bubble detachment point is zero, so its thermal equilibrium quality is:

$$x_{ed} = -\frac{h_l - h_d}{h_{fg}}$$

and the Levy' s relation[13] between x and x_e:

$$x = x_e - x_{ed} \exp\left(\frac{x_e}{x_{ed}} - 1 \right)$$

6) By energy balance location of the onset of annular flow:

$$z_{an} = \frac{dG}{4q^{"}} \cdot \left(h_f - h_{in}\right) + \frac{dG}{4q^{"}} \cdot \left(h_{fg} x_e\right)$$

7) The initial liquid film thickness at the onset of annular flow:

$$d_{an} = 1 - \frac{d\sqrt{a}}{2}$$

III. Results and Discussion

The water CHF experimental data of KAIST Data Bank including Zenkevich et. al.[15], Thamson & Macbeth[16], Tong et. al., Maylinger, and KAIST are collected, which cover the ranges below:

Exit quality		>	0.1	
Flow rate	180	~	5300	$kg / m^2 - s$
Pressure	0.5	~	17.7	MPa
Subcooling enthalpy	150	~	1500	kJ / kg
Diameter	5	~	37.5	mm

Figure 2 shows the prediction trend of the present model for flow, pressure, subcooling enthalpy, diameter, L/D, and exit quality. The prediction uncertainty is gradually bigger as the inlet subcooling approaches the saturation point. This should be interpreted that the annular flow at the low subcooled inlet condition could not be developed well due to the relatively short distance to form the annular flow. The mechanism of this annular flow formation might be different due to the entrance effect and the relatively less bubble exist in the channel by the cut of the memory effect in the normal subcooled boiling process. Total 3026 data from the different source of experiments are calculated in CHF prediction with the mean of 0.98 and root mean square error of 0.11, as shown in Table 1 and Figure 3. To have a reasonable range for void fraction at the onset of annular flow, those calculated void fraction range are less than 0.20 are discarded. The void fraction at the onset of annular flow range fell into the range of 0.20~0.85 for water CHF data. For the superficial velocity of gas, Wallis[18] proposed another formula for onset of annular flow:

$$j_g = 0.9\left[\frac{gd(r_f - r_g)}{r_g}\right]^{1/2} \tag{13}$$

The model is also checked by that prediction of the starting point of annular flow for the same data. In comparison with Taitel et. al.'s formula, the number of converged data is lower and scattering is higher, as shown in Table 2.

IV. Conclusion

A mechanistic dryout prediction model in uniformly heated vertical tube is suggested by using the churn-to-annular flow transition criterion to calculate CHF at saturated flow condition. The following conclusions can be drawn:

(a) The accurate prediction of the initial condition using the churn-to-annular flow transition criteria could improve the prediction accuracy and extend the applicable range of the experimental data.

(b) The void fraction at the onset of annular flow range fell into the range of 0.20~0.85 for water CHF data.

(c) Taitel et al.'s Churn-to-annular flow transition criteria shows better prediction results than other's.

(d) The present model predicts well at the broad experimental ranges and has the complete convergence characteristics.

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NOMENCLATURE

C	concentration of liquid droplets in vapor core flow [kg m^{-3}]
C_{eq}	concentration of hydrodynamic equilibrium state [kg m^{-3}]
C_{fi}	interfacial friction factor
C_o	drift coefficient
d	tube diameter [m]
D	deposition rate of droplets [kg m^{-2} s^{-1}]
E	entrainment rate of droplets [kg m^{-2} s^{-1}]
g	gravitational acceleration [m s^{-2}]
G	mass velocity [kg m^{-2} s^{-1}]
G_f	liquid film flow rate [kg m^{-2} s^{-1}]
G_l	liquid flow in vapor core [kg m^{-2} s^{-1}]
h_f	enthalpy at saturation [kJ kg^{-1}]
h_{fg}	latent heat of vaporization [kJ kg^{-1}]
h_{in}	enthalpy at inlet [kJ kg^{-1}]
j_g	vapor superficial velocity [m s^{-1}]
k	mass transfer coefficient [m s^{-1}]
L	heated length [m]
p	pressure [MPa]
q''	heat flux [kW m^{-2}]
R	radius of tube [m]
Re	Reynolds number
u	velocity [m s^{-1}]
V_{gj}	drift velocity [m s^{-1}]
x	flow quality
x_{eq}	quality in hydrodynamic equilibrium state
x_{ex}	exit quality
x_e	thermal equilibrium quality
x_{ed}	thermal equilibrium quality at the bubble detachment point
Y_f	distance perpendicular to the wall [m]
z	axial distance [m]

Greek letters

a	void fraction

Subscripts

an	onset of annular flow

d	liquid film thickness [m]	f	liquid
d_C	critical liquid film thickness [m]	g	vapor
m	viscosity [kg m^{-1} s^{-1}]	w	wall
r	density [kg m^{-3}]		
s	surface tension [N m^{-1}]	***Superscripts***	
t	shear stress [N m^{-2}]		
y ,y'	entrainment parameters	+	non-dimensional mark

Table 1. Prediction results for the various experimental data source

Source	NUMBER	MEAN	STD	RMS.
Zenkevich et. al.	2337	0.999	0.100	0.100
Thamson & Macbeth	479	0.883	0.125	0.172
Tong et. al.	93	0.946	0.091	0.106
Era et. al.	44	0.996	0.088	0.088
KAIST	40	0.972	0.040	0.049
Maylinger	33	0.897	0.068	0.123
All Data	3026	0.978	0.112	0.114

Table 2. Prediction results with different formula for the onset of annular flow

Formula of	NUMBER	MEAN	STD	RMS
Taitel et. al.	3026	0.98	0.112	0.114
Wallis	2625	0.96	0.114	0.120

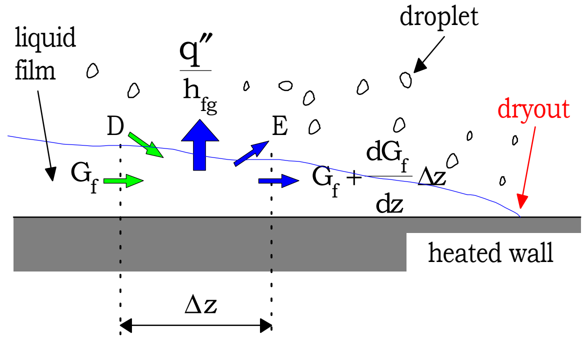

Figure 1. Control volume of the model

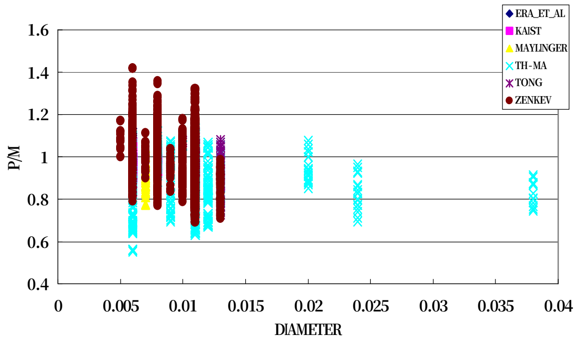

Figure 3. Predicted vs. measured critical heat flux

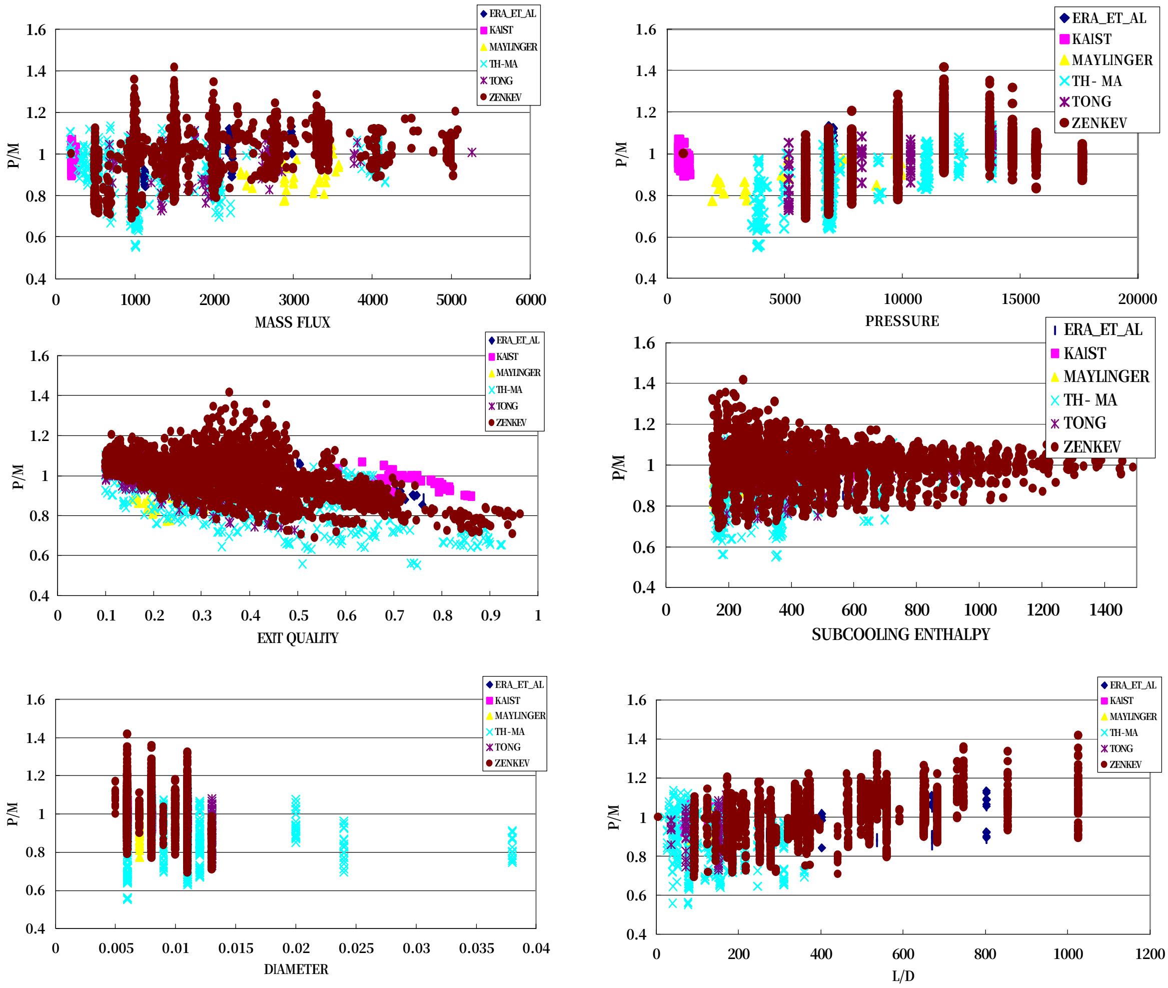

Figure 2. Prediction trend of present model for mass flux(kg/m^2·s), pressure(kPa), exit quality, subcooling enthalpy(kJ/kg), diameter(m) and length-to-diameter ratio