



Multiplicity and stability of boiling on a thin cylinder with heat generation



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ABSTRACT

A theoretical investigation was conducted to explore multiplicity and stability of boiling on a thin cylinder with different heat generations. The steady temperature distributions of the boiling on the cylinder were calculated under different boundary conditions and heat generations, and multiplicity phenomena were found in the boiling distribution diagram. In the multiplicity regions with proper cylinder length, there can be two or three steady temperature distributions with different boiling modes. In addition, the linear stability analyses were employed to investigate boiling system, and the maximum eigenvalue was derived to determine the stability of steady distribution. The obtained maximum eigenvalue distribution was shown to correlate well with the steady temperature and heat flux distributions, and the multiplicity phenomena also existed in the boiling stability diagram. In the multiplicity region, only one steady temperature distribution of the boiling was unstable with positive eigenvalue, while the others were stable with negative eigenvalue. Compared with available experimental results, the present model can very well explain the multiplicity and stability of boiling on the wires or fins.

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1. Introduction

Boiling on a cylinder [1,2] was very widely investigated following the Nukiyama's work, and it can be used as research foundation for many other applications. Boiling modes appearing on a cylinder are usually film, transition and nucleate boiling under various conditions. Since there is great difference among different boiling modes, the boiling mode distribution and the steady temperature distribution play an important role in heat transfer performance and stability characteristics. Lee and Lu [3] investigated two-mode boiling including nucleate and film boiling on a horizontal heating wire. Lu et al. [4] observed large bubble and explosive small bubble boiling on very small wires. Zhukov and Barellko [5] studied the nonuniform steady states of the boiling process in the transition region between the nucleate and film regimes. By a simple power-law type of the heat transfer coefficient for each mode, the steady temperature distributions were derived for various configurations [6,7].

Stability of boiling also remarkably affects the heat transfer performance of boiling on a cylinder. Kovalev and Rybchinskaya [8]

conducted a nonlinear stability analysis on fin boiling, and calculated the Lyapunov's function value for equilibrium distributions. Liaw and Yeh [9,10] analyzed the stability of one boiling mode on a fin with isothermal boundary condition. Lin and Lee [11] contributed a linear stability analysis on the steady-state solution for multi-mode boiling on a straight spine, a plate and an annular fin without heat generation [12]. Krikis et al. [13] conducted a multiplicity analysis on the solution structure of longitudinal fins subject to multi-boiling with isothermal boundary condition. Lu et al. [14] provided a theoretical investigation to understand the stability of boiling on annular fin surfaces with different boundary conditions. Available literature considered the stability of boiling on fin or cylinder without heat generation. However, boiling on cylinder with heat generation has wide applications, and associated multiplicity phenomena and stability performance should be further analyzed.

In this work, an attempt was made to investigate the steady temperature distribution and stability of boiling on thin cylinders with heat generation. The steady temperature distribution characteristics were investigated under different boundary conditions and heat generations, and the boiling distribution diagrams were further described with multiplicity phenomena. A linear stability analysis was proposed to analyze the boiling stability of the steady

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Nomenclature

A	surface (m^2)
a	heat transfer coefficient ($-$)
C_p	specific heat capacity ($\text{J kg}^{-1} \text{K}^{-1}$)
D	diameter (m)
h	boiling coefficient ($\text{J m}^{-2} \text{K}^{-1} \text{s}^{-1}$)
I	current (A)
j	boiling mode ($-$)
k	thermal conductivity ($\text{W m}^{-1} \text{K}^{-1}$)
L	length (m)
N	heat transfer exponent ($-$)
q	heat flux ($\text{J m}^{-2} \text{s}^{-1}$)
R	resistance (Ω)
S	circumference (m)
T	temperature (K)
t	time (s)

Greek symbols

β	Lagrange multiplier ($-$)
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θ	dimensionless temperature ($-$)
ρ	density (kg m^{-3})
ρ_r	electrical resistance (Ωm)
τ	dimensionless time ($-$)
η	Lagrange multiplier ($-$)
λ	eigenvalue ($-$)
Φ	perturbation ($-$)

Subscripts

1	film boiling
2	transition boiling
3	nucleate boiling
CHF	critical heat flux
MHF	minimum heat flux
ref	reference characteristic
sat	saturation state

distribution, and the boiling stability diagram was further compared with the distribution diagram.

2. Governing equation

Fig. 1 shows the schematic of analytical model for boiling on a thin cylinder with diameter D and length L . In present investigation, the cylinder root is fixed on a wall with temperature T_w , while the cylinder end is insulated. For low Biot number, the energy equation of the cylinder is stated as follows:

$$\rho C_p A(x) \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left[k(T) A(x) \frac{\partial T}{\partial x} \right] + [q_g - q(T)] S(x) \quad (1a)$$

$$T(0) = T_w, \quad k \partial T / \partial x|_{x=L} = 0 \quad (1b)$$

where $A = \pi D^2/4$, $S = \pi D$, q denotes boiling heat transfer flux, and q_g is heat generation.

Boiling heat transfer flux q is stated as:

$$q(T) = h(T - T_{sat}) \quad (2)$$

where T is cylinder surface temperature, and T_{sat} is liquid saturation temperature. As a normal assumption [15], the curve of q versus T is taken as an S-shape curve with critical heat flux (CHF) and minimum heat flux (MHF) points connecting the nucleate boiling and film boiling branches. At $T < T_{CHF}$ or $T > T_{MHF}$, the boiling is in nucleate boiling (N) or film boiling mode (F), whose $\partial q(T)/\partial T > 0$. At $T_{CHF} < T < T_{MHF}$, the boiling is in transition boiling mode (T), whose $\partial q(T)/\partial T < 0$. We denote number 1–3 for F, T and N boiling mode, respectively.

Assuming constant thermal properties of the cylinder, the dimensionless form of Eq. (1) is given as:

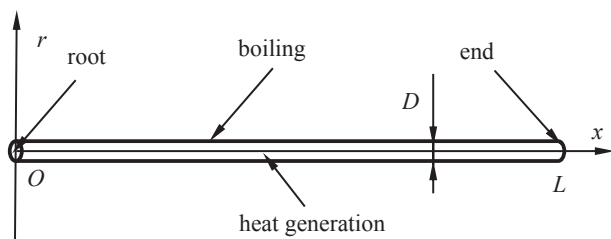


Fig. 1. Schematic of boiling on a thin cylinder.

$$\frac{\partial \theta}{\partial \tau} = \frac{\partial^2 \theta}{\partial X^2} + F(\theta) - M(\theta) \quad (3a)$$

$$\theta(0) = \theta_{b1} = \text{const}, \quad \partial \theta / \partial X|_{X=L_X} = 0 \quad (3b)$$

where $\theta = \frac{T - T_{sat}}{T_{ref} - T_{sat}}$, $X = \frac{x}{D^{1/2} D_0^{1/2}}$, $L_X = \frac{L}{D^{1/2} D_0^{1/2}}$, $M(\theta) = \frac{4D_0 h \theta}{k} = \frac{4D_0}{k(T_{ref} - T_{sat})} q$, $F(\theta) = \frac{4D_0}{k(T_{ref} - T_{sat})} q_g$, $\tau = \frac{\alpha t}{D_0^2}$, D_0 is reference length, and T_{ref} is reference temperature. Obviously, both boundary condition and heat generation play critically important roles in solving the dimensionless equation.

For simplification, heat generation is assumed to be produced by an applied constant current, and could be expressed as the follows:

$$F(\theta) = \frac{4D_0}{k(T_{ref} - T_{sat})} q_g = \frac{16\rho_r D_0 I^2}{\pi^2 k D^3 (T_{ref} - T_{sat})} \quad (4)$$

where ρ_r denotes specific resistance. For boiling on fin without heat generation, $I = 0$.

Normally, the specific resistance and conductivity of metallic cylinder as a function of temperature were first calibrated before experiments, and then the heat flux and wall temperature were obtained by the current and voltage measurements, consequently the boiling heat transfer coefficient and associated constant can be derived [1,18].

In present article, methanol boiling on a cylinder surface is considered to calculate heat transfer coefficient with a power-law form, $h_j = a_j (T - T_{sat})^{N_j}$, $a_j = 10, 1.976 \times 10^9, 600$ and $N_j = 0.735, -3.51, 1.5$ for film, transition, and nucleate boiling modes, respectively, and $q_{CHF} = 1.07 \times 10^6 \text{ W m}^{-2}$, $T_{CHF} = 20 \text{ K}$, $q_{MHF} = 2.46 \times 10^5 \text{ W m}^{-2}$, and $T_{MHF} = 90 \text{ K}$ [16]. The resistance of cylinder is assumed to be, $\rho_r = 4.33471 \times 10^{-14} T^2 + 2.19691 \times 10^{-10} T - 1.64011 \times 10^{-8} \Omega \text{m}$. Besides, $k = 401 \text{ W m}^{-1} \text{K}^{-1}$, $D_0 = 2.1 \times 10^{-3} \text{ m}$, and $T_{ref} - T_{sat} = 90 \text{ K}$.

3. Steady temperature distributions and multiplicity phenomena

For steady boiling on a thin cylinder, $\partial \theta / \partial \tau = 0$, and Eq. (3a) can be expressed as:

$$\frac{\partial^2 \theta}{\partial X^2} = \frac{\partial \theta}{\partial X} \cdot \frac{\partial}{\partial \theta} \left(\frac{\partial \theta}{\partial X} \right) = \frac{1}{2} \frac{\partial}{\partial \theta} \left(\frac{\partial \theta}{\partial X} \right)^2 = M(\theta) - F(\theta) \quad (5)$$

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