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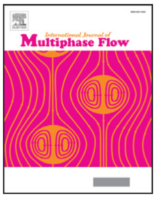

Predicting the critical heat flux in pool boiling based on hydrodynamic instability induced irreversible hot spots

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ABSTRACT

A new model, based on the experimental observation reported in the literature that CHF is triggered by the Irreversible Hot Spots (IHS), has been developed to predict the Critical Heat Flux (CHF) in pool boiling. The developed Irreversible Hot Spot (IHS) model can predict the CHF when boiling methanol on small flat surfaces and long horizontal cylinders of different sizes to within 5% uncertainty. It can also predict the effect of changing wettability (i.e. contact angle) on CHF to within 10% uncertainty for both hydrophilic and hydrophobic surfaces. In addition, a linear empirical correlation has been developed to model the bubble growth rate as a function of the system pressure. The IHS model with this linear bubble growth coefficient correlation can predict the CHF when boiling water on both flat surfaces and long horizontal cylinders to within 5% uncertainty up to 10 bar system pressure, and the CHF when boiling methanol on a flat surface to within 10% uncertainty up to 5 bar. The predicted detailed bubble grow and merge process from various sub-models are also in good agreement with the experimental results reported in the literature.

1. Introduction

Boiling has been widely applied in many important industrial applications, such as in the nuclear industry and high power electronic systems, as an efficient way to manage the excessive thermal load. The ability of a boiling system to dissipate heat at different surface temperatures has been extensively investigated since the early 1970 s and is often represented by the well-known Nukiyama curve (i.e. the boiling curve). The boiling curve suggests that there is a maximum heat flux (i.e. Critical Heat Flux – CHF) condition at the end of the nucleate boiling regime. When the imposed heat flux is larger than the CHF, the surface temperature will increase significantly to the so-called burnout temperature, which is typically well above the softening point or even the melting point of the metal surface, often causing system failure. Therefore, significant efforts have gone into understanding and predicting CHF through both experiments and simulations. The recent advancements in measurement and imaging techniques have made it possible to visualise and quantify the conditions near CHF directly. These experimental results show that the process behind the initiation of the CHF is contradictory to most of the postulated physical processes behind existing models. Furthermore, these results provide clues and insights for the development of new CHF models based on more rigorous physics. This paper firstly reviews the existing models and discusses their limitations and contradictions to the observed physical process. It then presents a new model which is better capable of predicting the CHF conditions.

2. Review of existing models and their limitations

The existing models used to predict the CHF in pool boiling can be broadly grouped into four different types of models: (i) the hydrodynamic instability models, (ii) the hydrodynamic force imbalance model, (iii) the macrolayer dryout models, and (iv) the dry spots models. Different types of models are derived based on different postulated CHF initiation mechanisms. The formulae, the key underlying assumptions, and the limitations of these models are reviewed in turn.

2.1. The hydrodynamic instability models

The hydrodynamic instability models have been the most popular models since their first appearance in 1950 by Kuteladze (Kutateladze, 1950) who derived it through non-dimensional analysis. The model was then further developed into many widely adopted analytical models, such as Zuber's model (Zuber, 1959),

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Lienhard and Dhir's model (Dhir and Lienhard, 1973) and many other semi-empirical models which aim to correct the Zuber's model by multiplying it with extra terms obtained through curve fitting to experimental data (e.g. El-Genk and Guo, 1993; Brusstar and Merte, 1994). Yagov (2014) provided a comprehensive review of this group of models and concluded that some of the critical assumptions could not be justified or were contradictory to the experimental observations.

The detailed assumptions behind this group of models can be found in the literature (Zuber, 1959; Carey, 2008; Liang and Mudawar, 2017). The key controversial assumptions are presented here.

1. The vapour columns are assumed to be cylindrical and distributed based on the two-dimensional wave patterns predicted by the Rayleigh–Taylor (RT) instability. Zuber (1959) used the critical wavelength ($\lambda_{C,\,RT}$) and the most dangerous wavelength ($\lambda_{D,RT} = \sqrt{3}\lambda_{C,RT}$) to calculate the upper and lower limit in CHF. Dhir and Lienhard (1973) used the most dangerous wavelength ($\lambda_{D,\,RT}$). The radius of the vapour column (R_v) in both models are assumed to be equal to one quarter of the unstable wavelength.
2. The Kelvin-Helmholtz (KH) instability wavelength (λ_{KH}) imposed on the columns in Zuber's model is assumed to be equal to the Plateau-Rayleigh instability wavelength for circular jets ($\lambda_{KH,Z} = 2\pi R_v$). λ_{KH} in the Lienhard and Dhir's model is assumed to be equal to the most dangerous wavelength predicted by the RT instability theory ($\lambda_{KH,L} = \lambda_{D,RT} = \sqrt{3}\lambda_{c,RT}$).

The KH instability analysis for a vertical interface between the liquid phase and vapour phase suggests the critical velocity difference (u_c) between the liquid phase and the vapour phase can be calculated by Carey (2008):

$$u_c = |\bar{u}_l - \bar{u}_v| = \left[\frac{2\pi\sigma(\rho_l + \rho_v)}{\rho_l\rho_v\lambda_{KH}}\right]^{1/2} \tag{1}$$

where $\bar{u}_l$ and ρ_l are the average velocity and the density of the liquid phase flow; $\bar{u}_v$ and ρ_v is the average velocity and the density of the vapour phase flow; σ is the surface tension; and λ_{KH} is the critical wavelength to induce the KH instability.

Since $\rho_l \gg \rho_v$, to satisfy the continuity equation, $u_c \cong u_v \cong [\frac{2\pi\sigma}{\rho_v\lambda_{KH}}]^{1/2}$

According to assumptions 1 and 2,

$$q''_{CHF} = \rho_v u_v h_{lv}\left(\frac{A_v}{A_s}\right) = \rho_v h_{lv}\left(\frac{\pi}{16}\right)\left[\frac{2\pi\sigma}{\rho_v\lambda_{KH}}\right]^{1/2} \tag{2}$$

where A_s is the surface area; A_v is the vapour column area; and h_{lv} is the latent heat.

The RH instability analysis (KH instability for a horizontal surface with negligible interface velocity: $\bar{u}_l = \bar{u}_v = 0$) suggests:

$$\lambda_{D,RT} = 2\pi\left[\frac{3\sigma}{(\rho_l - \rho_v)g}\right]^{1/2} \tag{3}$$

The arithmetic average of the upper limit (i.e. $\lambda_{KH} = \lambda_{C,RT}$) and the lower limit (i.e. $\lambda_{KH} = \lambda_{D,RT}$) can be calculated by Eq. (4a) (Zuber, 1959):

$$q''_{CHF,Z} = \frac{\left(q''_{CHF,Z,upper} + q''_{CHF,Z,lower}\right)}{2} = 0.138\rho_v h_{lv}\left[\frac{\sigma(\rho_l - \rho_v)g}{\rho_v^2}\right]^{1/4} \tag{4a}$$

Zuber (1959) also introduced a convenient way to get the average value, which is using $\lambda_{C,\,RT}$ as the instability wavelength but scale down the coefficient. The result is Eq. (4b) and is widely adopted as the Zuber's model to calculate the CHF in literature.

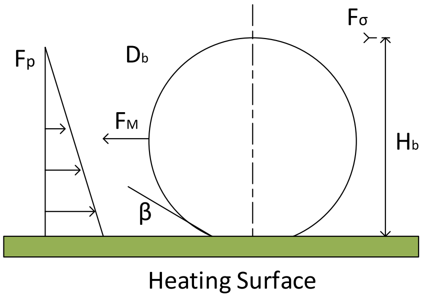

Fig. 1. Force-imbalance on bubbles in CHF in Kandlikar's model.

$$q''_{CHF,Z} = 0.131\rho_v h_{lv}\left[\frac{\sigma(\rho_l - \rho_v)g}{\rho_v^2}\right]^{1/4} \tag{4b}$$

Lienhard and Dhir's model (Dhir and Lienhard, 1973) can be written as a function of Zuber's model such that: $q''_{CHF,LD} = 1.14q''_{CHF,Z}$.

Both analytical hydrodynamic instability models are susceptible to the choice of the KH wavelength ($q_{CHF}'' \propto \lambda_{KH}^{-1/2}$) and the area ratio between the columns and surface ($q_{CHF}'' \propto A_v/A_s$). Both models used the instability wavelength from the RT instability as the KH instability wavelength. However, the RT instability is only a special case of the KH instability where a high-density fluid is on top of a low-density fluid with negligible interfacial velocity, which is quite different from the actual flow conditions in boiling. The sizes and the separation distances of vapour columns used in these two models also cannot be justified. As indicated by Yagov (Yagov, 2014), the experimental results reported by various researchers contradict the sizes and the separation distances of the vapour columns used in these two models. Many experimental visualizations (Ahn and Kim, 2012; Chu et al., 2013, 2014) also clearly show that the vapour generated under high heat flux conditions (including the CHF condition) is encapsulated into large coalesced bubbles which repeatedly form and detach from the surface. In addition, the bubble sizes were shown to reach diameter much larger than $\lambda_{D,\,RT}/4$. Therefore, the steady-state condition behind the hydrodynamic instability models is not an accurate representation of the actual physical process.

Despite these difficulties, the analytical models developed by Zuber, and, Lienhard and Dhir can predict the CHF in saturated pool boiling on smooth horizontal surfaces to within 20% accuracy, which is about the level of scattering in data of this type (Carey, 2008). The most accurate models used to predict CHF conditions are mostly semi-empirical correlations modified from the Zuber's model (Fang and Dong, 2016). These models usually incorporate an empirically fitted function of the contact angle which is overlooked in both Zuber's model and the Lienhard and Dhir's model. This suggests that the existing analytical hydrodynamic instability model is likely to be an incomplete model which should be revised to represent the experimental observations more accurately.

2.2. Hydrodynamic forces imbalance model

Kandlikar (2001) developed a model based on the hydrodynamic behaviour of the interface of a single detached bubble to predict the q''_{CHF}. Kandlikar considered the force balance for a single large bubble, as shown in Fig. 1. Kandlikar hypothesised that the CHF occurs when the repulsive force coming from the liquid evaporation on the interface surpasses the surface tension force and gravitational forces along the evaporation direction so that the

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