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Review

Pool boiling critical heat flux (CHF) – Part 2: Assessment of models and correlations

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A B S T R A C T

This paper is the second part of a two-part study on pool boiling critical heat flux (CHF) from flat surfaces. While the first part reviewed different CHF models and associated mechanisms and parametric trends, the present part is dedicated to the assessment of both models and correlations. The assessment is based on a new consolidated CHF database consisting of 800 data points amassed from 37 sources, and includes 14 working fluids, pressures from 0.0016 to 5.2 MPa, orientation angles from 0 to 180°, and contact angles from 0 to 113°. It is shown that a modified hydrodynamic instability model and the interfacial lift-off model provide the best predictions for CHF from horizontal, upward-facing surfaces. Modified with a correlation for surface orientation effects, the same models also provide the best predictions for inclined surfaces. However, all models and correlations lose accuracy at or near the downward-facing orientation, which points to the need for more data and improved understanding of near-wall interfacial behavior for these orientations. Finally, recommendations are provided for prediction of contact angle effects.

Contents

1. Introduction

Recent performance advances in applications such as high-performance computers, electrical vehicle power electronics, avionics, and directed energy laser and microwave weapon systems, have led to unprecedented increases in power density. With

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Nomenclature

A	area
c_p	specific heat at constant pressure
g	gravitational acceleration
H	wall thickness
h_{fg}	latent heat of vaporization
k	thermal conductivity; coefficient
P	pressure
P_c	critical pressure
Pr	Prandtl number
q''_{CHF}	critical heat flux
R_i	individual gas constant
S	thermal activity parameter
T_{sat}	saturation temperature

Greek symbols

α	contact angle
θ	surface orientation angle
υ	kinematic viscosity
ρ	density
σ	surface tension

Subscripts

asy	asymptotic
exp	experimental
f	liquid
g	vapor
h	high
l	low
max	maximum
$pred$	predicted
w	surface

fan-cooled heat sinks and single-phase liquid cooling schemes faltering in their ability to maintain acceptable device temperatures, interest has shifted to two-phase cooling schemes, which capitalize on the coolant's both latent and sensible heat rather than sensible heat alone. For over three decades, efforts at the Purdue University Boiling and Two-Phase Flow Laboratory (PU-BTPFL) have focused on research and development of two-phase cooling schemes [1,2], including two main categories of thermal solutions: (i) passive (pump-free) schemes, consisting of capillary-driven devices (heat pipes, capillary pumped loops, and loop heat pipes) [3] and pool boiling thermosyphons [4], and (ii) flow-boiling schemes, including falling film [5], channel flow boiling [6–8], mini/micro-channel flow boiling [9–11], jet-impingement [12–14], and spray [15–17], as well as hybrid cooling schemes combining the merits of mini/micro-channel flow and jet impingement [18]. Key to successful implementation of any of these schemes is the ability to predict boiling performance, especially critical heat flux (CHF). The present study is focused entirely on CHF prediction for pool boiling, which is the simplest, most prevalent, and most reliable of the different cooling schemes.

Accurate prediction of pool boiling CHF is crucial to the safety and reliability of applications spanning many industries. Since the 1940s, many efforts have been pursued to both understand CHF mechanisms and develop theoretical and empirical predictive tools. As discussed in Part I of this study [19], five main categories of theoretical models have been proposed: *bubble interference model* [20], *hydrodynamic instability model* [21–23], *macrolayer dryout model* [24], *hot/dry spot model* [25,26], and *interfacial lift-off model* [27]. Meanwhile, there have also been efforts to modify these models either theoretically or empirically in pursuit of higher predictive accuracy by accounting for effects not addressed in the original models. Overall, most modifications are based on the hydrodynamic instability model [21–23] and an early formulation based on dimensional analysis [28], which have both achieved great success in predicting pool boiling CHF. Unfortunately, most predictive tools have been validated only for a few working fluids and relatively narrow ranges of operating conditions, which inevitably limits their overall applicability. Addressing these limitations and pursuit of a more universal predictive methodology are two primary motivations for the present study.

This paper is the second part of a two-part study addressing pool boiling CHF. Part I [19] provided a detailed review of CHF models and correlations, as well as CHF trigger mechanisms. This second part will assess 18 popular CHF models and correlations using a consolidated database that the authors have amassed from 37 sources, which consists of 800 data points for 14 different fluids, and includes variations in pressure, orientation, and contact angle. Using this consolidated database, some of the models and correlations are assessed beyond their original validity ranges. Based on the assessment, the most accurate predictive methods are identified and recommended.

2. Previous CHF predicting methods

As discussed in Part I [19], pressure, surface orientation, and contact angle can have significant influences on CHF. The pressure effects are reflected in thermal properties, especially vapor density and latent heat of vaporization, which are accounted for in most models and correlations. However, surface orientation and contact angle are not accounted for in most original predictive tools, meaning these tools must be modified to address these effects. A key limitation of most predictive tools is that they were developed exclusively for the horizontal, upward-facing surface orientation ($\theta = 0°$). While different methods have been proposed to account for other surface orientations, most are purely empirical and based on data obtained only at atmospheric pressure. In addition, most pool boiling CHF papers fail to address or even mention contact angle effects.

The 18 CHF models and correlations assessed in the present paper are divided into three groups. The first group is specific to the upward-facing surface orientation and includes, aside from the original dimensionless analysis formulation of Kutateladze [28], (1) *hydrodynamic instability models* of Zuber et al. [21–23], Lienhard and Dhir [29,30], and Wang et al. [31] (which also accounts for effects of reduced pressure), (2) *bubble interference model* of Rohsenow and Griffith [20], (3) *macrolayer dryout model* of Haramura and Katto [24], (4) *hot/dry spot model* of Yagov [25], and (5) *interfacial lift-off model* of Mudawar et al. [27] and Guan et al. [32]. The second group consists of correlations incorporating the effects of orientation angle alone at atmospheric pressure, and includes studies by El-Genk and Bostanci [33], Vishnev [34], Arik and Bar-Cohen [35], Brusstar and Merte [36,37], and Chang and You [38]. The third group consists of correlations incorporating the effects of both orientation angle and contact angle at atmospheric pressure, and includes works by Kirichenko and Chernyakov [39], Theofanous and Dinh [26], Kandlikar [40], and Liao