TREATMENT OF NUCLEATION AND BUBBLE DYNAMICS IN HIGH HEAT FLUX FILM BOILING

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ABSTRACT

This paper reports results of a study of nucleate boiling on a thin liquid film at high heat fluxes. A method to identify and characterize active nucleation sites based on processing of heater surface temperature and local cooling/heating rate is developed. This method is applied to a select dataset of infrared thermometry imaging. The nucleation site density data are compared other literature data and correlations. A large variation and significant uncertainty was observed. Besides that, a range of data analysis is performed. The nucleation temperature, nucleation site distribution, nucleation rate, as well as the neighboring nucleation site distance was analyzed. The extracted data are used to benchmark fundamental modeling assumptions used in current treatments of nucleation and bubble dynamics, particularly for their applicability in high heat flux conditions. Attention is paid on stochastic, dynamic behaviors of nucleation. This scoping study also aims to provide suggestions on design of validation experiments and data processing procedures that enable assessment of model form uncertainty in wall boiling models at high heat fluxes.

KEYWORDS
Nucleate Boiling; Thin Liquid Film; High Heat Flux; Vapor Bubble; Nucleation Sites

1. INTRODUCTION

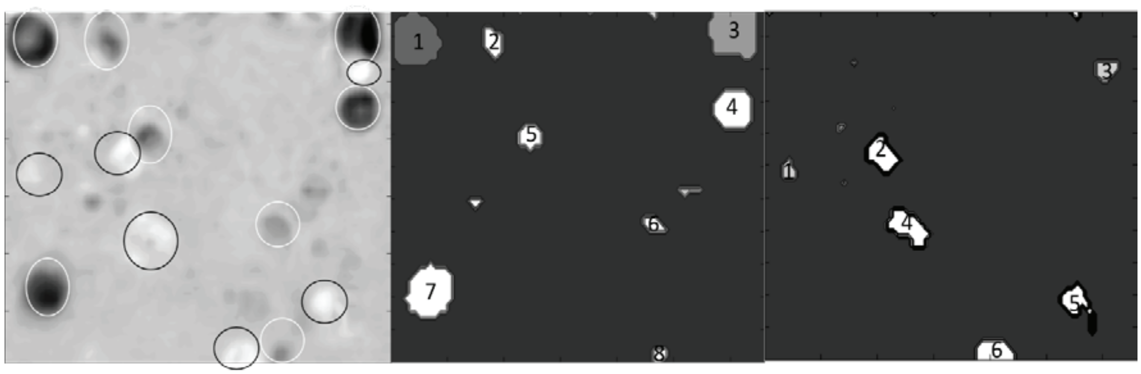
This paper is concerned with state-of-the-arts modeling and simulation capability to predict two-phase flow (TPF) and boiling heat transfer (BHT) processes. The modern capability referred here is based on two-fluid time or space averaged models, ranging from one-dimensional Eulerian-Eulerian formulation, to sub-channel analysis (SCA), and multi-dimensional Computational Multiphase Fluid Dynamics (CMFD) codes [1] [2] [3]. In the two-fluid models conservation equations of mass, momentum and energy are completed by a set of constitutive laws for inter-phase exchanges of mass, momentum, and energy. For example, wall boiling heat transfer models are used to derive closure relationships for mass exchange (evaporation), and energy sources (heat partitioning). Currently, the wall boiling model is based on nucleation parameters including nucleation site density (NSD), bubble departure diameter (BDD), and bubble departure frequency (BDF).

It is noted that the SCA and CMFD capabilities are developed and applied for Thermal-Hydraulic analysis in the Consortium for Advanced Simulation of Light Water Reactors (CASL). Previous work including sensitivity/uncertainty study conducted by CASL researchers on nuclear reactor thermal-hydraulics methods identified high sensitivity of the prediction to boiling heat transfer models, particularly to nucleation site density [4] [5]. In fact, it is well established that a physics-based sound understanding of nucleation behavior is essential to modeling and prediction of boiling thermal-hydraulics. However, a

bubble's thermal growth and departure duration may last for 2-3 frames. To avoid double counting of nucleation sites, an interval of five frames is chosen for the identification of active nucleation sites. Each dataset is based on processing of 500 frames.

To measure nucleation rate, consecutive TG frames were used. A large negative TG threshold is used to filter out the already nucleated sites and ensure that in each frame only newly activated nucleation sites are taken into account. For the data presented in this paper, nucleation events activated in each of consecutive 100 frames (which is around 31ms) were detected and used to evaluate nucleation rate.

The measurement of nucleation temperature T_{NUC} follows a similar procedure, using a high negative TG threshold to detect nucleation event in frame (N+1). For the detected nucleation event, its nucleation center position (and related pixel [i,j]) can be approximated. T_{NUC} is the pixel [i,j] temperature T_{SUR} (N,i,j) in the IRT frame (N).



(a) temperature gradient (TG) (b) identified "cooling spots" (c) identified "heating spots"
Figure C1. Identification of active nucleation sites through "cooling spots" and "heating spots" in a temperature gradient snapshot (heat flux=1943 kW/m^2)

Another uncertainty source came from possible omitted nucleation events between two frames. Since the nucleation events is millisecond level, and the time interval between two frames is 0.31ms, it is possible that a nucleation event that occurred between two frames might be lost. This part of uncertainty needs to be quantified by comparing the TG data with bubble image data in near future which has a much higher frequency. Noted that the uncertainty analyzed above were for the detection of nucleation events and nucleation location. The uncertainty of temperature measurement is dependent on the accuracy of measurement and the geometry and emissivity of the substrate and metal film. This part of uncertainty is not discussed in this paper.

It is noted that the data processing procedure and analysis algorithms are still under development, refinement and verification. Uncertainty quantification of both measurements and data processing are subject of a next report.