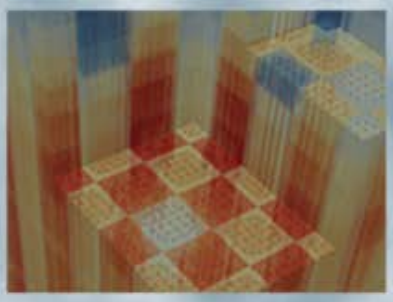
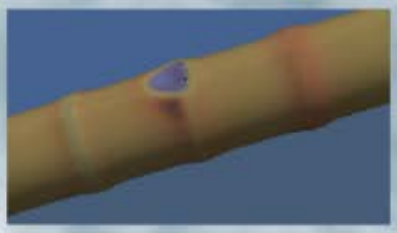
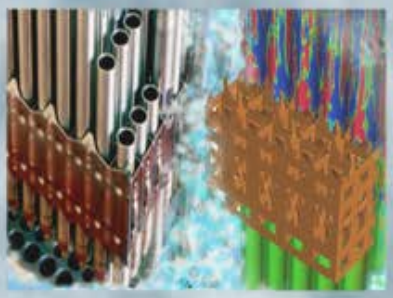
CASL-U-2015-0253-000

Treatment of Nucleation and Bubble Dynamics in High Heat Flux Boiling







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TREATMENT OF NUCLEATION AND BUBBLE DYNAMICS IN HIGH HEAT FLUX BOILING

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Introduction

Nucleate boiling is a highly efficient and desirable cooling mechanism in high-power-density systems. At a certain point of high heat flux, the departure of nucleate boiling (DNB) would occur, leading to substantial reduction of the system's coolability. A sound physics-based understanding of nucleation behavior is essential to the modeling of boiling thermal-hydraulics and prediction of DNB.

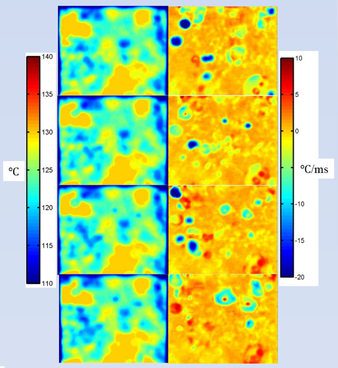
Current model introduced active nucleation site density (NSD) as derived from photographic images. The NSD is a static and averaged parameter. In order to represent dynamics and obtain nucleation rate, the bubble departure frequency (BDF) is introduced. In this way, the nucleation behavior in current model is treated as **static**, **deterministic**, and **independent**. Note that those experiments were conducted under **low to medium heat fluxes.**

BETA experiment (Theofanous et al., ETFS-2002) provides direct visualization of nucleation under **high heat flux**. By processing infrared (IR) images using a novel approach, we can accurately detect nucleation events. The new observations, point to the need for a new treatment of nucleation and bubble dynamics in high heat flux boiling, that is **stochastic**, **dynamic** and **collective**.

T.G.Theofanous, T.N.Dinh, J.P.Tu and A.T.Dinh, "The boiling crisis phenomenon: Part II: dryout dynamics and burnout," Experimental Thermal and Fluid Science, vol. 26, no. 6-7, p. 793–810, 2002.
T.N.Dinh and T.G.Theofanous, "Nucleation phenomena in boiling," Multiphase Science and Technology, vol.15 no.1-4, 2003.
T.G.Theofanous and T.N.Dinh., "High heat flux boiling and burnout as microphysical phenomena: mounting evidence and opportunities," Multiphase Science and Technology, vol. 18, no. 1, pp. 1-26, 2006.

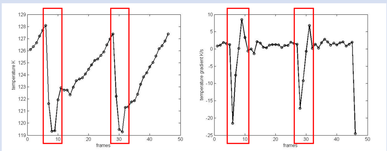
Identification Method

High frequency (3267 Hz) IR imaging provides the dynamic temperature on the heater surface. Temperature gradient can be obtained by getting the temperature difference from two consecutive frames. The large negative gradient (cooling spot) indicate the beginning of nucleation while the positive gradient (heating spot) could indicate the termination of nucleation. In this way, the nucleation events and its dynamics can be captured.



Temperature *Temperature gradient*

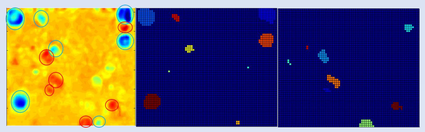
Identification of active nucleation sites



Temperature *Temperature gradient*

The nucleation event is considered to initiate when a sudden temperature drop is observed and to terminate when temperature begin to increase

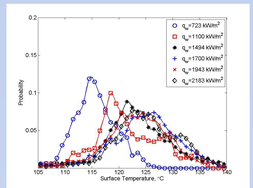
Hierarchical clustering method is employed to distinguish and track individual cooling and heating spot of each frame



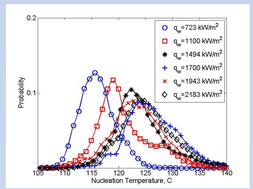
Identification of cooling and heating spot

Active nucleation sites of each frame can be identified, so the NSD can be calculated. Nucleation rate can also be obtained by tracking the nucleation events of each frame. In this way, the location of each nucleation event and its corresponding nucleation temperature can be obtained.

I. Nucleation temperature



Surface temperature distribution

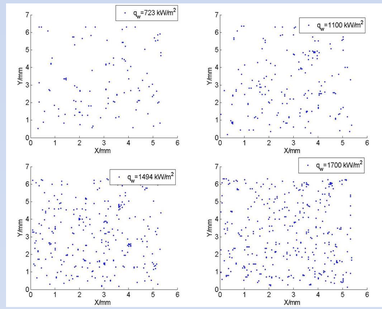


Nucleation temperature distribution

It is observed that the distribution of nucleation temperature are close with the distribution of surface temperature. This indicate nucleation is not necessarily associated with high temperature region

Nucleation occurrence does not correlate to the local heater temperature. This insight is to be contrasted with thermodynamic arguments that relate nucleation to heater's surface superheat. Temperature independence of nucleation on otherwise uniform heater suggests that nucleation is stochastic event.

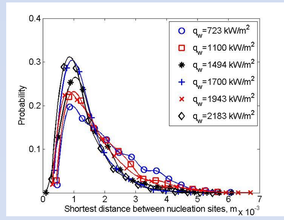
II. Nucleation site distribution



Spatial distribution of accumulative nucleation sites

Instead of active at a few fixed sites, there are ample thermodynamically "qualified sites" for nucleation. However, for a given moment, only a few of the "qualified sites" are activated. This showed a dynamic pattern of nucleation.

The nearest distance between nucleation showed a Poisson-like distribution. With increasing heat flux, the distribution sharpens as the mean distance decreases



Distribution of nearest distance between neighboring active nucleation sites

Summary Remarks

The above insight is foundational to proposing a new treatment of nucleation. In fact, the current common use of static and averaged in time and space NSD and BDF simplifies calculation procedure, while also trip off significant information. The situation is similar to steady-state coarse-mesh treatment of turbulence.

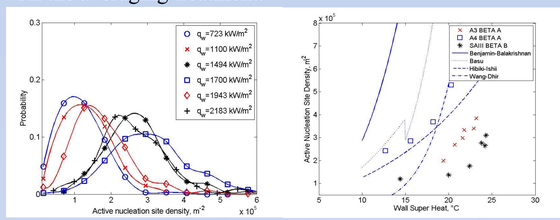
The insights derived from nucleation data analysis suggest that a new modeling framework for nucleation in boiling is needed to provide a more physical treatment. This treatment must allow for dynamic, stochastic and collective behavior of nucleation.

Such new treatment should be validated and calibrated under multiple experiment datasets including history data.

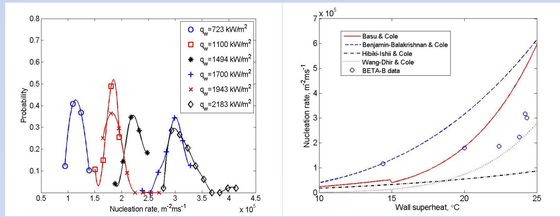
Related Validation and Verification work and corresponding Uncertainty Quantification work should also be compatible with such new treatment. There is still much challenging yet exciting future work needs to be done.

III. Nucleation site density and nucleation rate

The number of active nucleation sites under independent frames as well as the nucleation rate over a certain time period can be obtained. The averaged value of the distribution can be compared with currently widely used model. Noticed valuable information would be strip off with the averaging treatment.



Active nucleation site density and the comparison with models



Nucleation rate and the comparison with models

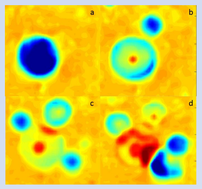
A wide spread of NSD values over time also indicates a highly dynamic and stochastic character of nucleation pattern.

Nucleation rate (as well as NSD) calculated by different models varies greatly especially under high heat fluxes.

Large model form uncertainty has been identified in current model. Caution must be exercised in applying "classical" wall boiling models to predict nucleation parameters at high heat fluxes.

IV. Nucleation sites interaction

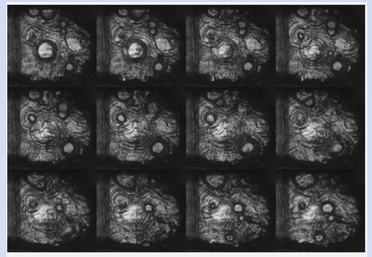
Interaction between neighboring nucleation sites can be clearly observed in both IR image of heater surface temperature gradient and optical image of bubble.



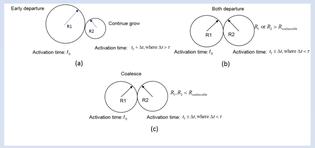
Effect of nucleation sites interaction on heat transfer

Heat transfer is observed to deteriorate in the contact region between bubbles

Bubble diameter would be constrained by neighboring sites. Early departure and bubble coalescence can be observed



Effect of nucleation sites interaction on bubble dynamics



One model to describe nucleation site interaction

Interaction may play an important role in DNB and corresponding heater burnout, and should be incorporated in the nucleation model.

The interaction between nucleation sites under high heat flux is both common, and limiting for nucleation and bubble dynamics, suggesting a collective behavior that makes nucleation a thermo-fluid process as opposed to thermodynamic condition.

Acknowledgements

This work was supported by the Consortium of Advanced Simulation of Light Water Reactors (CASL). The BETA experimental program was supported by the Department of Energy NERI and NASA Fluid Physics program at the University of California-Santa Barbara. The authors thank Professor T.G. Theofanous and Dr. J.P. Tu for their seminal contribution in the BETA project.

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