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IR thermographic investigation of nucleate pool boiling at high heat flux

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Nucleate water pool boiling at high heat flux was investigated on the 25 μm titanium and stainless-steel heaters at atmospheric pressure. A high-speed IR thermographic camera was applied to measure the rapidly changing transient temperature field, which served as input data for calculating the transient local heat flux distributions by solving a 3-dimensional (3-D) inverse heat conduction problem (IHCP). A phenomenon of hot spot was observed at the irregular active bubble site characterized by a longer waiting time and a higher activation temperature compared to a regular active nucleation site. The results show that the temperature of the hot spot can significantly exceed the temperature of the heater in its surroundings and remains present on the boiling surface even after the bubble departure. The calculations have shown a strong reduction of the local heat flux at the spot, which represented a potential for the beginning of the boiling crisis.

Étude thermographique IR d'ébullition libre nucléée à flux thermique élevé

Mots clés : Ebullition libre ; Flux thermique élevé ; Spot chaud ; Problème de conduction de chaleur inverse

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Nomenclature

c	constant parameter according to the discrepancy principle
c_p	specific heat of the foil [J kg^{-1} K^{-1}]
d	upper bound of the measurement noise [K]
h_{air}	heat transfer coefficient at the bottom side of the heater [W m^{-2} K^{-1}]
$J(q)$	continuous objective functional
∇J	gradient of the objective functional
n	outer normal of the boundaries Γ
p_k	conjugate search direction in the CG iteration k
q	heat flux along the boiling boundary [W m^{-2}]
$q(x,t)$	heat flux at the fluid-heater interface along spatial and temporal coordinates [W m^{-2}]
q_h	heat flux along the heated boundary [W m^{-2}]
q_k	estimated heat flux in the CG iteration k [W m^{-2}]
q_{paint}	heat flux through the high emissivity paint [W m^{-2}]
q_r	heat flux along the remaining boundary [W m^{-2}]
q_0	initial guess for the unknown heat flux [W m^{-2}]
q'	thermal energy generation rate [W m^{-3}]
S_k	solution of the sensitivity problem in the CG iteration k
t	time [s]
$[0,t_f]$	observation time interval [s]
$T(x,t)$	calculated transient temperature field [°C]
T_b	boiling surface temperature [°C]
T_{heater}	temperature at the bottom of the foil [°C]
T_k	temperature solution in the CG iteration k [°C]
$T_m(x,t)$	observed transient temperature field [°C]
T_{paint}	temperature at the bottom of the high-emissivity paint [°C]
T_0	initial guess for the unknown temperature [°C]
T_∞	surrounding temperature [°C]
γ_k	conjugate coefficient in the CG iteration k
Γ_b	boiling boundary [m^2]
Γ_h	heated boundary [m^2]
Γ_r	remaining boundary [m^2]
Γ	given boundary [m^2]
δ_{foil}	thickness of the foil [m]
δ_{paint}	thickness of the high emissivity paint [m]
λ, λ_{heater}	thermal conductivity of the foil [W m^{-1}K^{-1}]
λ_{paint}	thermal conductivity of the high emissivity paint [W m^{-1}K^{-1}]
μ_k	search step length in the CG iteration k
ρ	density of the foil [kg m^{-3}]
ψ_k	solution of the adjoint problem in the CG iteration k
Ω	3-D computational domain [m^3]

1. Introduction

Nucleate boiling is a complex non-linear process. As it is one of the most effective ways of heat transfer in engineering, intensive modeling and experimental investigation have taken place in recent years in order to resolve its physical background. In order to explain the mechanisms of single bubble nucleation, growth and departure, different models of microlayer, macrolayer, and contact line evaporation have been introduced. These include theoretical approaches (Dhir, 2005; Kenning, 1999; Stephan and Hammer, 1996; Wayner, 1992) as well as numerical simulations (Genske and Stephan, 2006; Kunugi and Ose, 2014; Li et al., 2014, 2015; Sahu et al., 2015; Sanna et al., 2014; Son and Dhir, 2008; Wu and Dhir, 2011). All of these deal with the simplified phenomenon of isolated bubble growth while the interactions from the adjacent nucleation sites are neglected. The implementation of these models is for this reason limited to the less intensive boiling process of low heat flux. Experimental investigations are therefore still required to study boiling phenomena under high heat flux conditions.

During boiling process, rapid temperature changes and movement of liquid–vapor interface take place, which imposes the application of experimental techniques of high spatial and time resolution. Buchholz et al. (2006) conducted measurements with microsensors embedded in a 7 mm thick copper plate. Kenning and Yan (1996) observed 2-dimensional transient wall temperature field on 130 μm thick stainless-steel foil by liquid crystal thermography with a time resolution of 5 ms in water nucleate pool boiling. Demiray and Kim (2004)