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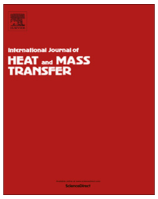

Transient boiling of water under exponentially escalating heat inputs. Part I: Pool boiling

Guan-Yu Su [a], Matteo Bucci [a,b,*], Thomas McKrell [a], Jacopo Buongiorno [a,*]

[a] Department of Nuclear Science and Engineering, Massachusetts Institute of Technology, Cambridge, MA 02138, USA
[b] CEA Saclay, DEN/DANS/DM2S/STMF/LATF, 91191 Gif-sur-Yvette Cedex, France

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ABSTRACT

This paper presents an investigation of transient pool boiling heat transfer phenomena in water at atmospheric pressure under exponentially escalating heat fluxes on plate-type heaters. Exponential power escalations with periods ranging from 5 to 100 ms, and subcooling of 0, 25 and 75 K were explored. What makes this study unique is the use of synchronized state-of-the-art diagnostics such as infrared (IR) thermometry and high-speed video HSV, which enabled accurate measurements and provided new and unique insight into the transient boiling heat transfer phenomena. The onset of nucleate boiling (ONB) conditions were identified. The experimental data suggest that ONB temperature and heat flux increase monotonically with decreasing period and increasing subcooling, in accordance with the predictions of a model based on transient conduction and a nucleation site activation criterion. Various boiling regimes were observed during the transition from ONB to fully developed nucleate boiling (FDNB). Onset of the boiling driven (OBD) heat transfer regime and overshoot (OV) conditions were identified, depending on the period of the power escalation and the subcooling. Forced convection effects have also been investigated and are discussed in the companion paper (Part II).

1. Introduction

Transient boiling heat transfer is important to the safety of nuclear reactors. Step inputs of reactivity in a nuclear reactor might result in a power excursion in which the heat generation in the nuclear fuel rises exponentially with time $q'''(t) \propto e^{t/\tau}$. The period of the exponential power excursion τ depends upon the size of the reactivity step. Large steps yield to periods that can be as short as a few milliseconds. The heat generated within the fuel is transferred to the water coolant which then starts to boil. The reactivity feedbacks caused by the heating (Doppler in the fuel and void in the coolant) represent an important mitigation mechanism for such accidents. Depending on the magnitude and the delay of these feedbacks, a safe conclusion to the accident is rapidly achieved or, in extreme cases, the fuel can melt, the molten material can be expulsed, fragmented and possibly lead to steam explosion. The time delay between heat generation within the fuel and its transfer to the coolant is key to determining the outcome of the accident, in particular for experimental reactors using highly enriched fissile fuel with a very low Doppler effect. This time delay depends on conduction heat transfer within the fuel, single-phase convective heat transfer and eventually transient boiling heat transfer in the coolant.

Transient boiling of water under exponentially escalating heat fluxes has been studied since the 1950s. Most of these investigations were carried out in pool boiling conditions, using ribbon [1,2] and wire [3–7] heaters. Some forced convection studies also exist for ribbon [8] and wire [9] heaters. Table 1 summarizes the experimental conditions and diagnostics of these earlier investigations.

All these studies used the same technique to determine the instantaneous heater average temperature and net heat flux to water. The average heater temperature was determined through measurement of the heater resistance, generally made of Platinum, Aluminum or Deltamax®, whose resistivity changes with temperature. The instantaneous net heat flux to water was determined as the difference between the power released by Joule heating $V(t)\cdot I(t)$ and the rate of change of the energy stored within the heater itself $C_h \cdot dT_h(t)/dt$. For thin heaters with a negligible thermal resistance [1,2,8], the average temperature on the boiling surface could be assumed equal to the average heater temperature. For relatively thick heaters [3–7,9], the temperature on the boiling surface could be determined by solving the unsteady thermal conduction

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* Corresponding authors at: Department of Nuclear Science and Engineering, Massachusetts Institute of Technology, Cambridge, MA 02138, USA. Tel.: +1 617 715 2336 (M. Bucci). Tel.: +1 617 253 7316; fax: +1 617 258 8863 (J. Buongiorno).

E-mail addresses: mbucci@mit.edu (M. Bucci), jacopo@mit.edu (J. Buongiorno).

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Nomenclature

Latin letters

a	thermal diffusivity $[m^2/s]$
A	area $[m^2]$
C	heat capacity [J/K]
c	speed of light (appendix) [m/s]
C_2	$=1.439 \times 10^{-2}$ (appendix) [mK]
Cp	specific heat [J/kgK]
e	uncertainty [K or W/m^2]
dt	time step (appendix) [s]
ΔT	temperature difference [K]
Fo	Fourier number $(= a\tau/L^2)$ [–]
h	heat transfer coefficient $[W/m^2K]$
I	current [A]
Ja	Jacob number $(= \rho_l Cp_l \Delta T_{sat}/h_{lv}\rho_v)$ [–]
k	thermal conductivity [W/mK]
L	thickness [m]
N_p	photons flux (appendix) $[phot/m^2 s\ m]$
nc	noise counts (appendix) [counts]
$ncounts$	IR camera counts (appendix) [counts]
n_f	focal number (appendix) [–]
p	pressure [Pa]
q''	heat flux $[W/m^2]$
q'''	energy source $[W/m^3]$
QE	quantum efficiency (appendix) [–]
R	fraction of heat flux to water [–]
R_c	contact electrical resistance [ohm]
r	radius [m]
t	time [s]
T	temperature [K]
V	voltage [V]
x	spatial coordinate [m]
y	spatial coordinate [m]
z	spatial coordinate [m]

Acronyms

CHF	critical heat flux
FDNB	fully developed nucleate boiling
FTIR	fourier transform infrared spectrometry
IR	infrared
IRC	IR camera
ITO	indium-tin oxide
HDAS	high-speed data acquisition system
DCPS	high-speed direct-current power supply
HSN	heterogeneous spontaneous nucleation
HSV	high-speed video
OBD	onset of boiling driven regime
ONB	onset of nucleate boiling
OV	overshoot

Greek letters

α	absorption coefficient (appendix) [1/m]
$\mathcal{E}$	thermal effusivity $[W\sqrt{s}/m^2K]$
ϵ	apparent emissivity [–]
λ	wavelength [m]
ρ	density $[kg/m^3]$
ρ	reflectivity (appendix) [–]
τ	exponential period [s]
τ	transmissivity (appendix) [–]

Subscripts

0	initial
atm	atmosphere
$bulk$	bulk
c	cavity or conduction
dc	dark current (appendix)
ew	empty well (appendix)
fw	full well (appendix)
h	heater (ITO)
ic	inertia-controlled
int	integration time (appendix)
l	liquid
onb	onset of nucleate boiling
$pixel$	pixel (appendix)
re	repeatability
s	substrate
sat	superheat
sub	subcooling
tot	total
te	temporal
v	vapor

equation in the heater, having the time dependent generation rate (Joule heating) as source term and the net heat flux to water as boundary condition at the boiling surface.

High speed video (HSV) was used to identify ONB and visualize the boiling process [1,5,6,8]. Piezoelectric hydrophones were used to detect ONB in subcooled conditions [3]. X-ray absorption was used to measure void fractions in transient flow boiling experiments [8].

In a transient pool boiling test it is typical to identify several characteristic features, i.e. the single-phase heat transfer regime, the onset of nucleate boiling (or boiling inception), the fully developed nucleate boiling regime and ultimately the boiling crisis. A brief summary of the previous work on and current understanding of each of these features is presented next.

1.1. Single-phase heat transfer

Transient non-boiling heat transfer is a well understood phenomenon. For short periods, typically smaller than 100 ms, the temperature rise on the heater surface is too fast for natural convection to develop and contribute to heat transfer [1–3,10]. Conduction is the leading heat transfer mechanism. Thus, transient conduction equations can be solved to determine the temperature on the heater surface and the temperature distribution in water. For longer periods, the temperature rise on the heater surface is slow. Buoyancy forces set the fluid in motion and natural convection supersedes pure conduction [3].

1.2. Onset of nucleate boiling

There is general agreement that the transient ONB superheat decreases with decreasing subcooling and increasing pressure, as implied by the steady boiling inception criteria, i.e. the Hsu's model [11]. Transient effects are also qualitatively clear. ONB superheat and heat flux decrease as the exponential period is increased. However ONB data reported in the literature are often very scattered and are not free from discrepancies, as explained next.

Rosenthal [1] was the first to identify the ONB conditions using a high-speed camera synchronized with measurements of voltage and current through a ribbon heater. Accordingly, the ONB

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