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A study on the mechanisms triggering the departure from nucleate boiling in subcooled vertical flow boiling using a complementary experimental approach

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ABSTRACT

New experimental observations on the trigger mechanisms for the departure from nucleate boiling in subcooled flow boiling in a vertical, rectangular channel with an inner diameter of 40 mm are presented. A critical review of available mechanistic models and trigger mechanisms is given and a comparison to the experimental results is presented. Experimental results are derived using a matrix of complementary measuring techniques to review the validity of the proposed mechanisms for flow boiling of Novec 649. Mass fluxes are in the range of 500–2000 kg m^{-2} s^{-1} and subcoolings range from 27 to 9 K. A conceptualization for a refined phenomenological modeling approach is presented, and possible future research discussed.

1. Introduction

The departure from nucleate boiling (DNB) and the accompanying critical heat flux (CHF) are among the most relevant phenomena in boiling heat transfer. A large number of correlations and models have been presented over the last decades, however the opinion on the actual trigger events of the transition is still divided. This can largely be attributed to the difficulties in experimentally accessing the relevant effects, as this requires analysis on a range of time and geometrical scales for several orders of magnitude each (from μm to m, and from μs to minutes), taking place in a highly complex multiphase flow. Still, many current models have been developed based mainly on photographic visualization studies, which have greatly helped in understanding the general vapor behavior but cannot yield information on a number of parameters deemed crucial in understanding the DNB transition. Accordingly, the mechanisms presented in many models lack actual experimental confirmation. To overcome this shortage, an approach was made using a matrix of five measuring techniques complementing each other in order to gain enhanced insight into phenomena in both the vapor and liquid phase, as well as heat transfer effects in the heater and the liquid phase and local properties in the high quality region close to the heater.

2. Current mechanistic models

To improve calculation of the critical heat flux over empirical models, so called phenomenological or mechanistic models have been developed based on physical mechanisms leading up to the CHF. These types of models offer a potentially higher validity than purely empirical ones, under the precondition that correct mechanisms have been identified. These models have so far mainly seen use in academia, while for industrial applications the use of empirical correlations is still favored [1]. However, a correct phenomenological description of the actual trigger mechanisms for the DNB may not only improve the accuracy of calculations but also help in defining measures to prevent or postpone the departure from nucleate boiling. Furthermore, the understanding of DNB trigger mechanisms is also of utmost importance for a correct formulation of models for computational fluid dynamics (CFD). Up to now, CFD modeling of the departure from nucleate boiling is still mainly based on available empirical correlations and blending modeling setting the CHF at predefined void fractions [2,3]. In the following paragraph, the three most recently used types of mechanistic models shall be presented and discussed. These are namely the *bubble crowding model*, the *sublayer dryout model* and the *interfacial lift-off model*.

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Nomenclature

Abbreviations

CFD	computational fluid dynamics	
CHF	critical heat flux	
DNB	departure from nucleate boiling	
HSP	high speed photography	
ONB	onset of nucleate boiling	
PIV	Particle Image Velocimetry	

Greek symbols

Δ_ρ	density difference	kg/m^3
δ_m	sublayer thickness	m
ϵ	void fraction	–
λ_{cr}	critical wavelength	m
π	Pi	–
ψ	turbulence correction	–
ρ_g	vapor density	kg/m^3
ρ_g''	modified vapor density	kg/m^3
ρ_l	liquid density	kg/m^3
ρ_l''	modified liquid density	kg/m^3
σ	surface tension	$N\,m^{-1}$
$\sigma_{v'}$	radial fluctuating velocity	ms^{-1}
τ_w	shear stress	Pa

Roman Symbols

$\dot{q}_{CHF}$	critical heat flux	W/m^2
$\overline{U}_f$	mean velocity of the liquid phase	ms^{-1}
$\overline{U}_g$	mean velocity of the vapor phase	ms^{-1}
a	empirical constant	–
a_1	empirical constant	–
a_2	empirical constant	–
a_3	empirical constant	–
a_L	two phase multiplier	–
c_D	drag coefficient	–
c_{PL}	specific heat of the liquid	$J\,kg^{-1}K$
d	tube diameter	m
d_b	bubble size	m
D_e	equivalent diameter	m
D_p	average bubble diameter)	m
G	axial mass flux	$kg/m^2\,s$
g	gravity	$m\,s^2$
G'	lateral mass flux due to turbulence	$kg/m^2\,s$
G_m	relative mass flux	$kg/m^2\,s$
h_f	saturated liquid enthalpy	$J\,kg^{-1}$
H_g	vapor layer thickness	m
H_l	liquid layer thickness	m
h_l	liquid enthalpy	$J\,kg^{-1}$
h_{fg}	enthalpy of evaporation	$J\,kg^{-1}$
h_{ld}	enthalpy at point of bubble detachment	$J\,kg^{-1}$
h_{LG}	latent heat of evaporation	$J\,kg^{-1}$
h_{SC}	subcooled heat transfer coefficient	$W/m^2\,K$
i_b	turbulent intensity at the bubbly layer edge	–
k	empirical constant	–
k_w	wave number	–
U_b	vapor blanket velocity	m
Re	Reynolds number	–
T_{sub}	liquid subcooling	K
T_L	temperature of liquid entering sublayer	K
T_{sat}	saturated liquid temperature	K
L_m	vapor blanket length	ms^{-1}
U_m	mean liquid velocity	ms^{-1}
v_s	liquid superficial velocity	ms^{-1}
v_v	local vapor velocity	ms^{-1}
v_{11}	radial velocity created by vapor generation	ms^{-1}
x_1	average qualities in the core region	–
x_2	average qualities in the bubbly layer	–

2.1. Near wall bubble crowding model

The *near wall bubble crowding* assumes the loss of quenching and subsequent CHF to be caused by a rising concentration of vapor bubbles near the heater surface, which prohibits turbulence in the bulk flow from penetrating the vapor layer and transporting fresh liquid to the heater surface. It is assumed that this happens at a critical vapor fraction in the vapor layer, which is derived from a geometrical balance of given bubbles, that begin to coalesce after reaching the critical vapor fraction. The mechanism was first proposed by Weisman and Pei [4], based on previous work by Hebel et al. [5] and Hebel and Detavernier [6]. The original model assumed homogeneous flow of vapor bubbles and liquid within the bubbly layer. Ying and Weisman [7] expanded the model to lower mass velocities, replacing the homogeneous flow model with a slip model taking into consideration the buoyancy effects of larger bubbles. Lim and Weisman [8] also applied the model to flow in channels with partial heating, while Yang and Weisman [9] further expanded the model for calculation of pre-CHF heat fluxes throughout the detached bubble region. The model was based mainly on a small number of visualization studies.

2.2. Sublayer dryout model

The *sublayer dryout model*, first introduced by Lee and Mudawar [10] based on an older model with similar mechanism by Haramura and Katto [11], has received increased attention over the last twenty years [12–15]. According to this model, CHF occurs when a liquid sublayer present under the vapor bubbles during nucleate boiling cannot be replenished from the bulk flow any more and evaporates, creating a dry spot on the heater surface. To overcome some inconsistencies of the original sublayer dryout model, Celata et al. [16] developed the *superheated layer vapor replenishment model*, which assumes a liquid layer at saturation temperature (superheated layer) close to the heater surface, that dries out at CHF and is replenished by a vapor blanket. The model was mainly developed for high mass fluxes and liquid subcoolings. Since a main assumption is an isolated layer of liquid close to the heater surface as the only possible position for vapor bubbles, the models authors [16] state a loss of validity when local thermodynamic conditions at CHF approach the saturated state of the liquid bulk. The model basics have mainly been developed from visualization studies on small scale experiments, such as the falling film evaporation study by Mudawwar et al. [17]. Experimental validation for the model on larger scale boiling experiments is scarce, mainly because the postulated thin sublayer is challenging to access with available measuring techniques.

2.3. Interfacial lift-off model

Another very recent model is the *interfacial lift-off model*. In sharp contrast to the sublayer dryout model, this model focuses on the global behavior of the vapor rather than local microscopic effects. Here, a periodic behavior of the vapor layer along the whole