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The role of disturbance waves in nucleate boiling in annular flow

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ABSTRACT

In annular two-phase gas-liquid flow, the liquid film on the wall consists of relatively quiescent *substrate* regions which are traversed by large amplitude, high velocity waves known as *disturbance waves.* The turbulent disturbance wave regions have relatively high average heat transfer coefficients (low average wall temperatures) compared to the (probably laminar) substrate regions. Nevertheless, there is evidence that nucleate boiling (necessitating a higher wall temperature) occurs first in the wave regions. This paper explores the hypothesis that wall temperature fluctuations due to turbulence in the disturbance waves are of sufficient magnitude to give localized triggering of nucleation sites and hence nucleate boiling. This hypothesis was explored using Computational Fluid Dynamics (CFD). The turbulence was modelled using wall-resolved LES. The results lend weight to the hypothesis that the nucleate boiling observed in disturbance waves is due to transient local high temperatures induced by the turbulence.

1. Introduction

Annular two-phase gas-liquid (or vapor-liquid) flow occurs in a wide range of industrial equipment (boilers, condensers, pipelines, etc.) and is characterized by the presence of a thin, wavy liquid film driven along the wall by the shear force exerted by the gas (or vapor) phase in the core [1]. The film/core interface is covered by a complex pattern of waves [2]. These waves are typically of two main types, namely *ripples* which are of small amplitude and cover the whole film surface and *disturbance waves.* The disturbance waves have amplitude of the order of 5–6 times the mean film thickness and travel along the interface at much higher velocity than do the ripples. Calculation of the mean heat transfer coefficient in annular flow based on mean film thickness and mean interfacial shear stress gives rise to a gross over-prediction of the coefficient [1] and it is evident that the intermittent nature of annular flow (and in particular the influence of disturbance waves) needs to be taken into account.

Detailed measurements of the shapes of disturbance waves were carried out by Hewitt and Nichols [3] using a fluorescence method and Jayanti and Hewitt [4] used this data to specify the geometry of a typical disturbance wave. Jayanti and Hewitt then used computational fluid dynamics (CFD) methods to determine the temperature distribution in the disturbance waves and in the substrate regions between the waves. It was found that the wave regions were turbulent and had a high heat transfer coefficient whereas the substrate regions were laminar and had a low coefficient. Moreover, the mean predicted heat transfer coefficient was in much better agreement with measured values than were values calculated based on the *mean* film thickness and shear stress.

The calculations by Jayanti and Hewitt [4] suggest that the wall temperature (for a given heat flux) would *fall* in the disturbance wave region and *rise again* when the disturbance wave passed. This would normally mean that the likelihood of nucleate boiling (i.e. evaporation by the formation of bubbles at the surface) was greater in the substrate region. However, this conclusion is contradicted by more recent experiments by Barbosa et al. [5] who observed that nucleate boiling occurred in the disturbance wave itself and was suppressed in the substrate regions. Possible explanations of this behavior include the following:

- *Reduction of pressure in the wave region*
  Because the core gas accelerates in order to flow over the wave, this implies a reduction in pressure in the wave region. One may associate this to a reduction in saturation temperature and an increased propensity to nucleation. Approximate calculations on the pressure change in passing from the substrate region to the wave peak indicate a value of the order of 500 Pa for the present results. This corresponds to a small fraction of a degree in saturation temperature and so this explanation is unlikely to account for the transient increase in intensity of nucleation which is observed
  It should also be recognized that the *shape* of the gas velocity profile changes as the gas flows from the relatively smooth substrate region to the rough wave region [6,7] this would increase the pressure change associated with the wave region but, even

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Nomenclature

Acronyms
CFD Computational Fluid Dynamics
HTC Heat Transfer Coefficient
LES Large Eddy Simulation
RANS Reynolds-Averaged Navier-Stokes
RMS Root-Mean-Square
SIMPLE Semi-implicit Method for Pressure-linked Equation
WLES Wall-Resolved Large Eddy Simulation

Subscript
f front
G gas phase
i, j, l the vector components in the *i*-th, *j*-th and *l*-th directions
m, n the index of velocity probe
peak peak of disturbance wave
sat saturation
sub substrate region of disturbance wave
t tail
wall wall surface

Symbols
Cp heat capacity
Cr Courant number
D pipe diameter
f_i interfacial friction factor
g gravitational acceleration
h_s sensible enthalpy
$k_{s,d}$ the equivalent sand roughness
Ls, Cs model constant
p pressure
Pr_t sub-grid scale Prandtl number
r, θ, *z* parameters of cylindrical coordinates
Re Reynolds number
S rate-of-strain tensor
L length
t time
T temperature
u velocity
U the average linear velocity
x, y, z the vector components in the x-th, y-th and z-th directions
y^+ dimensionless wall distance
δ the local film thickness
λ thermal conductivity
μ molecular viscosity
μ_t sub-grid scale turbulent viscosity
ρ density
ρ_{mm} correlation coefficient
σ viscous stress tensor
τ_i interfacial shear stress
τ_{ij} sub-grid scale stress
Δ local grid size
Δl the dimension of the grid cell at each location
Δt the maximum time step size or time duration
ΔT temperature difference

accounting for this additional complexity, the pressure change would give rise only to a small change in saturation temperature. Thus, reduction of pressure (and hence saturation temperature, is unlikely to be the cause of nucleation events observed by Barbosa et al. [5].

- *Bubble entrainment in waves*
The highly disturbed motion of the interface in the disturbance wave region can give rise to the entrainment of small bubbles [8] which may penetrate to the more highly superheated zone near the wall and trigger nucleation at existing centers there. However, Barbosa et al. [5] argued that nucleation still occurred underneath the disturbance wave region even when no entrained bubbles were observed in their experiments.
Temperature fluctuation occurs in flow of heat and fluid due to turbulence and to the intermittency of phase content at a given location. During the process of nucleate boiling, wall surface-temperature fluctuations occur associated with the formation and release of vapor bubble. Moore and Mesler [9] measured the heater surface temperature fluctuation during nucleate boiling, and found that, under some conditions, the temperature fell during formation of the bubble and then rose again bubble departure. And further measurement using other techniques e.g. small resistance thermometer [10,11], microthermocouple [12,13], thin film-wire thermocouple [14] and microheater [15], observed similar temperature variations in pool-, film- and nucleate-boiling regimes. Ideally, the wall temperature distribution in Barbosa's experimental setup should be measured to provide clear evidence for the impact of disturbance wave on nucleate boiling. Although today's technique, e.g. an array of microheater, allows temporally and spatially resolved temperature measurement, localization of microsensors along the disturbance waves that propagate dynamically still faces significant technical challenges.
In the present paper we propose a new hypothesis to explain why nucleation occurs underneath the disturbance wave. It seems probable that the disturbance waves are turbulent regions separated by laminar substrate regions [4]. The turbulence in the disturbance waves gives rise to a much higher *average* heat transfer coefficient (i.e. a lower average wall temperature) but there is a very important difference between the essentially laminar substrate regions and the turbulent wave regions. This difference is that (for a given heat flux) the wall temperature in the turbulent wave region may fluctuate due to the action of near wall turbulence. The magnitude of the fluctuations may lead to the triggering of nucleation sites in the wave region. These near wall turbulent structures, commonly named *turbulent streaks* are well known to people studying single-phase turbulent thermal boundary layers [16]. In the work described here, the influence of near-wall turbulence in the disturbance wave regions of a two-phase annular flow has been explored using CFD methods.
The rest of this paper is organized as follows. In Section 2, we present the details of our model. A discussion of our numerical results is provided in Section 3. Finally, Section 4 is devoted to concluding remarks.

2. Computational model

The work described in present paper used a wall-resolved Large Eddy Simulation (LES) to qualitatively illustrate the idea introduced here. The simulation considered is a single-phase model