Theoretical Models for Boiling at Microgravity

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Abstract

In this work initial results are presented on the theoretical modelling of the following aspects related to microgravity boiling: the rate of phase change at moving interfaces, the thermocapillary effect at the phase separating boundary, the influence of thermal effects on the Rayleigh – Taylor instability of a heated static vapour layer below its liquid and the formation of the liquid macrolayer beneath vapour bubbles.

1. Introduction

Despite many years of experimental investigation the predictability of microgravity boiling is yet impossible [1]. The classical formulas for peak heat flux [2, 3, 4] for example, can no longer define its actual values at reduced gravity levels. Indeed, the existing theoretical models have been specifically developed for ground-based applications. The critical wavelength of the Rayleigh – Taylor instability [5] is used [3, 4] for the estimation of the distance between vapour masses on a plane heater in the stage of developed nucleate boiling. The critical wavelength has a small value at earth conditions and becomes very large as the gravity level decreases (for the water/air system under gravity 10⁻⁴g₀, g₀ = 981 cm/s²) its value is equal to 160 cm). When the horizontal dimensions of a system are less then the value of the critical wavelength, the Rayleigh – Taylor instability does not occur since all perturbations are stabilized by surface tension. Because of the small heater areas used in the microgravity experiments performed up to now the existing theoretical models cannot be applied.

The focus of this work is related to interactions between the mechanisms of the thermocapillary and the Rayleigh – Taylor instability at the liquid-vapour interface in the case of low Bond numbers. The nonequilibrium rate of phase change is described using the irreversible thermodynamics. The influence of the nonequilibrium effect on the thermocapillary one is described in terms of the phenomenological mass transport coefficient. It is proven that at high heat flux in a very thin vapour layer the Rayleigh – Taylor instability is replaced by
the thermocapillary one if the mass transport coefficient is sufficiently small. A possible mechanism of the liquid macrolayer formation is discussed which is due to the thermocapillary instability of a residual vapour layer remaining on a heater after bubble break off.

2. Rate of phase change

To describe theoretically boiling in microgravity it is necessary to know precisely the thermal conditions at the interfaces. In studies on condensation and evaporation the rate of phase change is generally defined by the famous Hertz–Knudsen equation. For a flat interface, along which the liquid and the vapour temperatures are assumed to be equal, the Hertz–Knudsen equation [6] is

\[ J = \beta \left( \frac{M}{2\pi R T} \right)^{1/2} \left[ p_s(T) - p_0(T) \right] \]

where \( J \) is the nonequilibrium mass flux across the interface, \( M \) is the molecular weight of the vapour, \( p_s(T) \) is the saturation pressure at surface temperature \( T \), \( p_0(T) \) is the vapour pressure just beyond the interface, \( R \) is the universal gas constant and \( \beta \) is the constant accommodation coefficient. According to the theoretical considerations of the kinetic theory the value of \( \beta \) should be close to unity. However, reported experimental values are of order \( 10^{-3} - 10^{-1} \) and there also exist discrepancies among the experimental data of various investigations.

One can derive an equation for the kinetics of phase transition in the framework of irreversible thermodynamics. Assuming continuity of the temperature along the interface \( T_v = T_l \) (\( \approx T \)) Onsager's law suggests [7] that

\[ J = K [\mu_l(p_l, T) - \mu_v(p_v, T)] \]

Here \( K \) is the positive phenomenological coefficient, \( \rho_v \) and \( \rho_l \) are the densities of vapour and liquid respectively. \( J \) is the rate of phase change. By definition \( J = \mathbf{J} \cdot \mathbf{n} \), where \( \mathbf{J} = \rho_l (\mathbf{v}_l - \mathbf{v}_v) = \rho_v (\mathbf{v}_v - \mathbf{v}_v) \) is the mass flux vector at the interface, \( \mathbf{v}_l \) and \( \mathbf{v}_v \) are the velocities of the liquid and vapour at the interface, \( \mathbf{v}_v \) is the interface velocity and \( \mathbf{n} \) is the surface normal unit vector directed into the vapour phase. Equation (2) together with the definition of \( J \) show that the mass will leave the phase with the highest chemical potential toward that with the lowest one. Let us remark that if the temperature jump across the liquid-vapour interface is taken into account, then other transport coefficients (see [8]) appear in the phenomenological equation for the mass and energy fluxes because there exists then a new thermodynamic force \( \delta T = T_l - T_v \). In accordance with the requirements of irreversible thermodynamics the phenomenological coefficient \( K \) depends on the surface temperature \( T \) and the vapour pressure \( p_v \). Equation (2) can be interpreted as an approximation to the general mass flux equation where the thermodynamic force \( \delta T \) is neglected.

In (2) the liquid and vapour pressures \( p_l \) and \( p_v \) and the temperature \( T \) vary along the moving interface. Introduce now a function \( p_s(T) \) which relates the value of \( T \) to the corresponding saturation vapour pressure for a flat isothermal interface at a constant temperature \( T \). Assume further that for the liquid