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Technical Note

Condensation of a bubble train in immiscible liquids

H. Kalman *

Pearlstone Center for Aeronautical Engineering Studies, Department of Mechanical Engineering, Ben-Gurion University of the Negev, P.O. Box 653, Beer Sheva 84105, Israel

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Abstract

We previously developed a theoretical envelope model for single bubbles condensing in immiscible liquids, in which the convection outside the bubble is conducted through boundary layers at the front of the bubble and through the wake at the rear while the bubble accelerates, and the convection is dominated by heat transfer through the wake all over the bubble while the bubble is enveloped by its own wake at decelerating. In this paper the envelop model is extended for bubble train condensing in immiscible liquids by assuming that the envelopment occurs from start, i.e., the bubble is enveloped by the previous bubble's wake right after detachment from the nozzle. The experimental results for freon-113 and hexane bubbles condensing in water confirm the assumption for injection frequencies higher than 12 bubbles per second.

Keywords: Bubble train; Condensation; Envelop model; Injection frequency

1. Introduction

Condensation of bubbles rising in cold liquids (both miscible and immiscible) is a complicated problem to analyze. The condensation rate and the heat dissipation from the bubble are directly affected by three major parameters [1]: (1) The temperature difference of the condensing vapor and the surrounding liquid temperature, which is the driving force for the condensation; (2) the external thermal resistance due to the flow and heat transfer phenomenon in the condensing liquid near the bubble surface; and (3) the internal thermal resistance of the condensate that remains within the bubble (obviously for condensing in immiscible liquids – two-phase bubble). When the condensation rate is higher than the mixing rate of the noncondensible gases in the vapor, a third thermal resistance might be added [2].

Experimental studies with bubbles condensing in miscible liquids have been previously conducted by many researchers. Of a special interest is an old publication by Moalem et al. [3] in which the condensation rate of a continuous bubble train rising from a single nozzle was solved by an iterative, simultaneous solution of the coupled flow and temperature fields.

Previous researches of the author [4–7] led to a clear picture of the physical phenomena governing the process of bubbles condensation in immiscible liquids. The vapor appears as a sphere eccentrically positioned in the bubble at its top (see Fig. 1). The condensate film seems to adhere to the bubble surface, grow in thickness while the bubble condensates. Right after the bubble detached from the nozzle, it accelerate first and than decelerates. A viscous boundary layer extends over the upper surface of the bubble and a wake over its rear surface while accelerating. An "envelope" of vortices surrounds the bubble (the bubble settles into its wake), while decelerating. In a later paper [8] the envelope model was extended to condensation in miscible liquids by assuming that in this case the condensate mixes immediately in the surroundings and the bubble is not enveloped at any stage of its rise.

In this paper, the envelope model is extended further and generalized to include condensation of bubble trains, i.e., high frequency injection of bubbles, by assuming that

* Tel.: +972 8 6477099; fax: +972 8 6477101.
E-mail address: hkalman@bgumail.bgu.ac.il

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Nomenclature

C_D	drag coefficient
CFF	condensation of R-113 in subcooled R-113
c_p	specific heat, J/kg °C
f	frequency of injection, bubbles per second
g	gravitational acceleration, m/s^2
h	convection heat transfer coefficient, W/m^2 °C
h_{fv}	heat of vaporization, J/kg
k	thermal conductivity, W/m °C
Nu	Nusselt number $= (2Rh/k_L)$
Pr	Prandtl number $= (\mu c_p/k)_L$
R	radius of bubble, m
Re	Reynolds number $= (2RU_\infty \rho_L/\mu_L)$
$\bar{R}_f$	Nondimensional final bubble radius $= (R/R_0)$
T	temperature, °C
T_s	saturation temperature, °C
T_s^*	saturation temperature at partial vapor pressure, °C
T_∞	temperature of continuous liquid, °C
t	time, s
U_∞	instantaneous rise velocity, m/s

Greek symbols

α	fraction of noncondensibles
γ	angle from front stagnation point of two-phase sphere
δ_f	thickness of condensate film, m
ΔT	temperature difference $= (T_s - T_\infty)$, °C
θ	angle from front stagnation point of vapor sphere
μ	viscosity, kg/m s
ρ	density, kg/m^3

Subscripts and superscripts

f	condensate
L	continuous liquid
0	initial or front stagnation point
r	rear
v	vapor
–	nondimensional length, dividing by R_0

the bubble is enveloped by the previous bubble wake during the whole collapse process.

2. The theoretical model

The previously described models were developed for single particles injected to a column of subcooled liquid and condensate individually without mutual effects. In this paper we would like to examine the condensation rate of bubbles injected in high frequency – bubble train. For this case, we only assume that the previous model is valid, but the bubble is enveloped by the wake vortexes from start also in the acceleration zone. The bubble is not enveloped by its own wake, but with the shaded wake of the previously injected bubble. Here, only the relevant equations for the bubble train condensation in immiscible liquids will

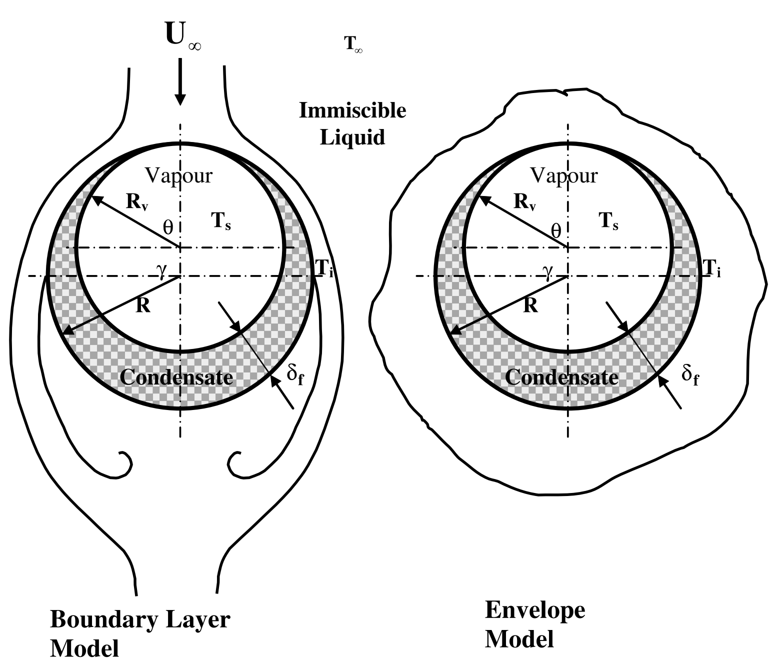

Fig. 1. A schematic diagram of the two-phase bubble and the nomenclature related to the bubble geometrical dimensions.