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Self-organising structure of bubble departures

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ABSTRACT

In the paper the self-organising structure of bubble departures from nozzle outlets has been investigated. In the experiment, bubbles were generated from brass nozzles with inner diameters of 1.1 mm. They were submerged in a glass tank filled with distilled water. Three different nozzle arrangements have been considered. Correlation coefficients between signals from laser-phototransistor and pressure sensors have been calculated. It has been shown that self-organising structures of bubble departures are formed by alternative bubble departures. Their appearance significantly modifies the frequency of bubble departures and prevents departing bubbles from the vertical coalescence. When bubbles are emitted from three nozzles, the alternative bubble departures are created over each pair of neighbouring nozzles. In case of three nozzles arranged in the row, the alternative bubble departures appear on the left and right side of the central nozzle. When bubbles depart from three nozzles arranged in corners of the triangle, the appearance of alternative bubble departures over each pair of nozzles leads to appearing clockwise and counter-clockwise direction of bubble departures. It has been shown that the stability of alternative bubble departures depends on the distance between nozzles, their arrangement and the air volume flow rate. Numerical simulations show that the diagonal liquid flow (created when bubbles depart from neighbouring nozzles not at the same time) establishes 'the communication' between two bubble chains. Such 'communication' modifies conditions of liquid flow over the nozzles, the time between successive bubbles and finally, establishes the alternative bubble departures.

1. Introduction

There are numerous physical parameters such as: physical properties of two phases, gas flow rate, gas pressure, height of the liquid and gravity conditions, which influence on the formation of bubbles. Hence, most of efforts have been devoted to the formation of bubbles from single nozzle or orifice plates [1,2]. When bubbles are generated from many nozzles or orifices, the complex interactions between them appear. Bubble interactions change the mean size of bubbles and liquid flow around them, and finally – the efficiency of gas–liquid mass transfer processes [3]. The mechanism of bubble interactions is not fully understood, therefore, it is still analysed [4,5]. Many methods have been used to investigate the formation of bubbles. Bubble behaviours have been investigated using: high-speed photography [6], an electrical triple probe [7], video techniques [8,9], holography [10], the phase-Doppler method [11], tomography and particle image velocimetry technique [12].

Bubble departures and behaviours may be periodic or chaotic. There are numerous papers describing the chaotic behaviours in the bubbling process [13–18]. The interactions between bubbles lead to more intensive occurrence of unpredictable bubble behaviours. In the paper [19], it has been shown that interactions between bubbles in vertical column cause the chaotic changes of volume fraction of the fluid. The chaotic bubble behaviours are connected with flow instabilities caused by bubble–bubble interaction [20] or coalescence between bubbles [21]. Interactions between bubbles during the formation of bubble chain are responsible for appearance of two [22] or three [23] characteristic frequencies of bubble departures. It has been shown that for different nozzle diameters the chaos appears in different ways [17]. It was found that the meniscus oscillations in orifice strongly affect the bubble behaviours [24,25]. In the paper [4], there have been analysed the interactions between bubbles generated from two adjacent micro-tubes. The analyses show that interactions and the coalescence time depend on the liquid properties, distance between tubes and gas flow rate. In the work [3], the coalescence rate of bubbles generated from two separated orifices has been studied and modelled. The coalescence has been analysed from the mechanistic and statistical approach.

The influence of hydrodynamic interactions between bubbles on their behaviour during departure has been observed in boiling

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Nomenclature

C	correlation coefficient
Cov	covariance function
D	diffusion coefficient
d	distance in phase space
f	frequency of bubble departures, [Hz]
H	Heaviside's step function
L	largest Lyapunov exponent, [bit/s]
m	number of examined points
N	the number of samples
p	pressure, [N/m^2]
q	air volume flow rate, [l/min]
S	spacing between nozzles
t	time, time of evolution, [s]
u	velocity, [m/s]
V	voltage, [V]
x	value of samples, bubble coordinate
y	bubble coordinate

Greek letters

ρ	density, [kg/m^3]
σ	standard deviation, surface tension
$\delta(\varphi)$	delta function at the phase interface
$\vec{n}$	the unit normal to the interface
φ	level function
κ	the surface curvature at the fluid interface
μ	viscosity

Indexes

g	gas, growth time
i, j	sample number
l	liquid
L	left
R	right
w	waiting time
p	time between departures of bubbles

experiment. In the paper [26], it has been shown that one of the reasons for nonlinear changes of properties of dynamics of interaction between nucleation sites, which occurs together with changes of initial spacing between them, is the hydrodynamic interaction between departing bubbles. In the paper [27], it has been shown that the interaction in the liquid (coalescence and hydrodynamic interaction) increases the frequency of bubble departures (promotes the growing bubble to depart). When it happens then the process of bubble departures becomes more predictable. It has been found out that the interaction between nucleation sites through the liquid stabilizes the process of bubble growth and its departure. In the paper [28], the coefficient of correlation of time changes of wavelet power spectrum for the given frequency, which was a measure of frequency synchronization in interacting cavities, has been analysed. It has been found that the hydrodynamic processes are responsible for synchronization of temperature changes in twin cavity. The conducted analysis confirms the existence of phenomenon of synchronization of bubble dynamics through the liquid flow induced by departing bubbles.

In this paper, it has been shown that the alternative bubble departures over the nozzle outlets introduce the order in the liquid flow and cause that bubbles depart synchronously. Therefore, such bubble departures can be treated as the self-organising process. It means the process in which the order is created by the interactions between components of the system. Results obtained for different nozzle arrangements and air volume flow rates will be compared with bubble behaviours over the single nozzle. Simple 2D model of liquid flow around the bubbles during their alternative departures over two nozzles will be used to explain the mechanism of bubble departures synchronization. Understanding the mechanism of hydrodynamic interactions between bubble sources (nucleation sites, nozzles and orifices) is important for prediction of occurrence of such processes as burnout or flow of bubbles in the column. Depending on the applications, the self-organising bubble departures may be treated as desirable or not desirable.

2. Experimental setup

In the experiment bubbles were generated from: one, two and three brass nozzles – each of them had the inner diameter of 1.1 mm and was located in the tank (400 × 400 × 700 mm) filled with distilled water. The distance between nozzles was changed from 3 mm up to 10 mm. Gas pressure fluctuations have been measured using the uncompensated silicon pressure sensor MPX12DP. In the laser-phototransistor system the semiconductor red laser with wave length of 650 nm, 3 mW, special aperture and phototransistor BPYP22 were used. The diameter of laser beam was ~0.2 mm. When the bubble was passing through the laser beam (about 3 mm above the nozzle outlet) the phototransistor sensor generated the signal of the low voltage level. The water temperature was 20 °C. The air volume flow rate was measured using the flow meter (KYTOLA OY, A-2k) and changed from 0.05 l/min to 0.3 l/min. The pressure and signal from phototransistor were simultaneously recorded using data acquisition system DT9800 with sampling frequency of 2 kHz. Samples were recorded during the 60 s for all air volume flow rates. Each nozzle had the own air supply system, which consisted of 2 dm^3 capacity air tank, the flow meter and the air pump. Bubble departures were recorded using the high speed Casio EX FX1 camera. The scheme of

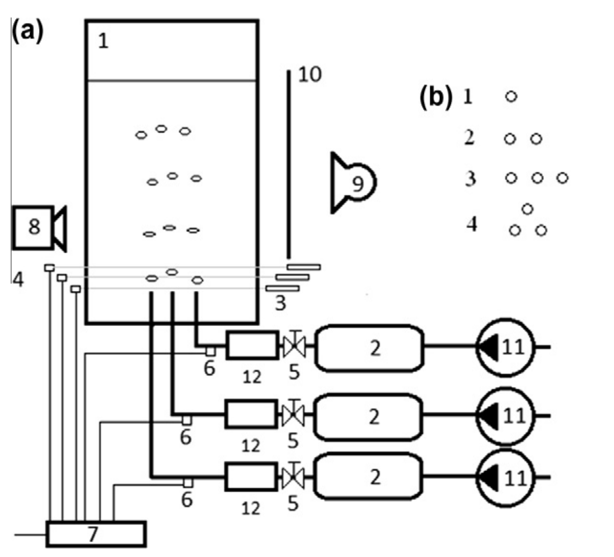

Fig. 1. Experimental setup. (a) Schema of experimental equipment. 1 – Glass tank (400 mm × 400 mm × 700 mm), 2 – air tank, 3 – laser, 4 – phototransistor, 5 – air valve, 6 – pressure sensor, 7 – computer acquisition system (DT9800 series USB Function Modules for Data Acquisition Systems), 8 – Casio EX FX1(600/1200 fps), 9 – light source, 10 – screen, 11 – air pump, 12 – flow meter (KYTOLA OY, A-2 k). (b) Nozzle arrangements.