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STUDIES ON THE DYNAMICS OF GAS BUBBLES IN MAGNETIZABLE NANOFLUIDS

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ABSTRACT

The paper presents results of experimental work on the dynamics of single gas bubbles in magnetizable nanofluids, with emphasis on the bubble frequency and average volume at departure. The effects of magnetic properties of the magnetizable nanofluid and of gradient of the applied magnetic field on bubble frequency and average bubble volume at departure were determined.

KEYWORDS

Magnetizable nanofluid, bubble dynamics, magnetic field

NOMENCLATURE

B [T]	magnetic flux density
D [mm]	injection hole diameter
D_{ech} [mm]	bubble equivalent diameter
f [s^{-1}]	bubble frequency
$\vec{g}$ [m/s^2]	gravitational acceleration
M_s [A/m]	saturation magnetization
δp [N/m^2]	relative pressure
V_b [mm^3]	bubble volume
ρ [kg/m^3]	density
τ_b [s]	bubble period

Subscripts and Superscripts

0	no applied magnetic field

1. INTRODUCTION

Over the last two decades, magnetizable nanofluids (known as magnetic fluids or ferrofluids) - a special class of nanomaterials, proved their unique performances and various applications in technical and biomedical fields, some of which were developed also in Timisoara [1-3].

Starting about a decade ago, researches regarding the use of magnetizable nanofluids as thermal fluid were carried out, the possible applications envisaging the use of convective and/or phase-change heat transfer modes, for both terrestrial and microgravity conditions [4-7]. For instance, in case of nucleate pool boiling regime, Gogosov and Simonovski showed that depending on the value and orientation of the magnetic field gradient with respect to gravity, the bubble generation frequency can be either increased (up to an order of magnitude), abruptly reduced or the vapor bubble generation can be even stopped, the results being reflected in the overall heat transfer coefficient [5].

The knowledge of heat transfer control mechanism in magnetizable nanofluids is of major importance in view of a proper design of future industrial applications and opened during the last years a new research area in the field of nanotechnology [8-9]. It is expected that both convective and phase-change heat transfer modes using magnetizable nanofluids will be characterized by higher heat transfer coefficients compared to that of the carrier (base) fluids. As boiling heat transfer mode shows a higher heat transfer coefficient compared to convective heat transfer mode, made necessary the study of the control mechanism of the former mode.

Recent results regarding the effect of magnetic field on the gas bubbles dynamics in magnetizable nanofluids are in accordance with the observations made during the boiling experiments of magnetizable nanofluids in similar magnetic field conditions [10-12]. Based on these results, a new experimental set-up was built, ready to be used for experimentation in both terrestrial and microgravity conditions (in a future parabolic-flight experiment) [11].

The paper presents a synthesis of the latest experimental results regarding the gas bubble dynamics in a magnetizable nanofluid in the presence of a non-uniform magnetic field.

2. EXPERIMENTAL SET-UP

2.1. Experimental bench

The experimental bench is presented in Fig.1. It was designed to study the phenomena related to the growth and departure of gas bubbles injected from a flat surface in magnetic liquid, when a magnetic field is applied.

The experimental apparatus consists of a cylindrical cell (9) with glass walls and Plexiglas bottom cap, in the center of which was drilled the gas injection hole. The topside of the cell is open to air. The cell can be easily removed from the operating position situated between the poles of electromagnet (7), thus, cells with holes of different diameters could be tested. The results referred to in the present paper are for hole diameters of: 0.3 mm and 1.5 mm.

The non-uniform magnetic field is generated using profiled electromagnetic poles (Fig.2). This positioning of the poles gives rise to a gradient of the magnetic field, ∇B, parallel with the gravitational field, $\vec{g}$. If the positioning is reversed we can get the opposite case: $\nabla B \| -\vec{g}$. In both cases the experimental cell was set at 50 mm from the bottom side of poles.

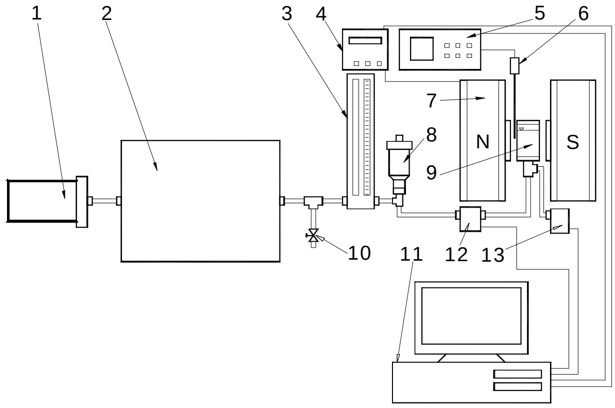


Figure 1.Experimental bench

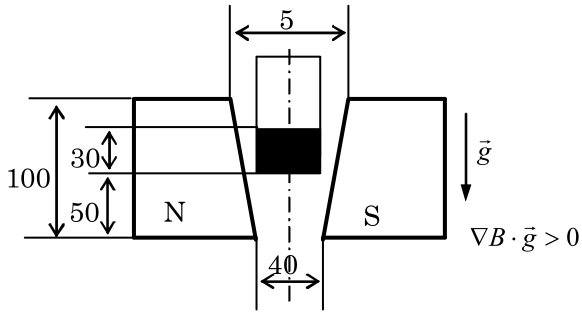


Figure 2. The positioning of the experimental cell

The magnetic flux density was measured along the symmetry axis of the air gap, with a 10 mm step. The field measurement was carried out using a Hall probe (6), connected to a Bell Gaussmeter (5). For instance, for a value of the magnetic flux density of 0.0865·T, we get a field gradient of 0.15 T/m when $\nabla B \| \vec{g}$. Simultaneously, the voltage corresponding to a set of data was measured. This type of measurement was repeated for a voltage ranging from 0 to 24 V (DC). Thus, a map of the value of magnetic field intensity in the axis of the air gap could be drawn and the dependence between the magnetic field intensity and the power supply voltage at the level of injection hole could be established. The same procedure was applied to measure the magnetic flux density for the case: $\nabla B \| -\vec{g}$. These dependencies were introduced later into the acquisition program, so during measurements only the signal of power supply was monitored and recorded, through a bridge rectifier (0-5 V).

The air is taken from the indoor ambient and introduced into a reservoir (2) for pressure variations compensation, using a mini-compressor (1). After opening the valve (10), the air passing through the capillary tubing system is injected into the magnetic liquid. The air flow rate is varied using a micrometer valve (8) and its value is measured using a flow rate transducer (12). The relative air pressure in the tubing system is measured with a manometer (4), while the relative pressure near the injection hole is measured by a pressure transducer.

The air flow rate, relative pressure near the injection hole and power supply voltage are input into a PC with a NI data acquisition system (11).

2.2. Magnetizable nanofluid samples

Two magnetic liquid samples of different saturation magnetization, denoted by LM_1 and LM_2, were prepared. Their composition, density and saturation magnetization are given in Table 1.

Table 1. Composition and properties of magnetic liquid samples

Sample	LM_1	LM_2
Carrier fluid	Hydrocarbon	Hydrocarbon
Magnetic nanoparticles	Magnetite	Magnetite
Density, ρ [kg/m^3]	1230	1470
Saturation magnetization, M_s [kA/m]	29.46	47.77

2.3. Measurements

The following parameters were monitored and measured:

- the instantaneous relative pressure near the injection hole (during the bubble growth and departure), measured by the differential pressure transducer (range: 0 – 12.5 mm H_2O, accuracy: ±1 %);
- the injected gas flow rate, measured by the flow rate transducer (range: 0 – 20 ml/min, accuracy: ± 1 %); all measurements were started from the same initial value of the inlet gas flow rate: 5 ml/min, irrespective of magnetic liquid sample.
- the voltage of the power supply, indicated by the panel voltmeter (range: 0-40 V DC).

At the start of each series of experiments we measured the ambient atmospheric pressure (measured by a barometer) and the ambient temperature.

The data acquisition was carried out using a National Instruments (Lab 1200/AI) data acquisition system and LabView software was used to produce the data acquisition, storage and primary analysis program. Usually, 1 000 samples/s were recorded for time periods of (2 – 10) s, depending on the case. Each measurement was repeated several times before recording, to avoid particular behavior to affect data interpretation.

3. RESULTS AND DISCUSSION

The recorded data allowed the following parameters to be calculated:

- average bubble frequency versus magnetic flux density,
- average bubble volume versus magnetic flux density.

The variation of the relative injection pressure measured near the injection hole corresponds to the formation and departure of gas bubbles from the hole. Thus, by measuring the time period between two peaks of $\Delta p(\tau)$ we get the bubble emission period, τ_b, and the bubble frequency results:

$$f = \frac{1}{\tau_b} \quad (1)$$

By averaging the value of the measured flow rate over the acquisition period we get the average gas flow rate. The average bubble volume is obtained:

$$V_b = \frac{Q}{f} \quad (2)$$

The results are compared in reduced values by the zero magnetic field corresponding values, denoted by f_0 – bubble frequency and V_{b0} – bubble volume.

When the magnetic field orientation is $\nabla B \| \vec{g}$, irrespective of the hole dimension the average bubbles frequency is increased up to 20-25 % (Fig. 3.a). The average bubble volume decreases with the same ratio as shown in Figure 3.b.

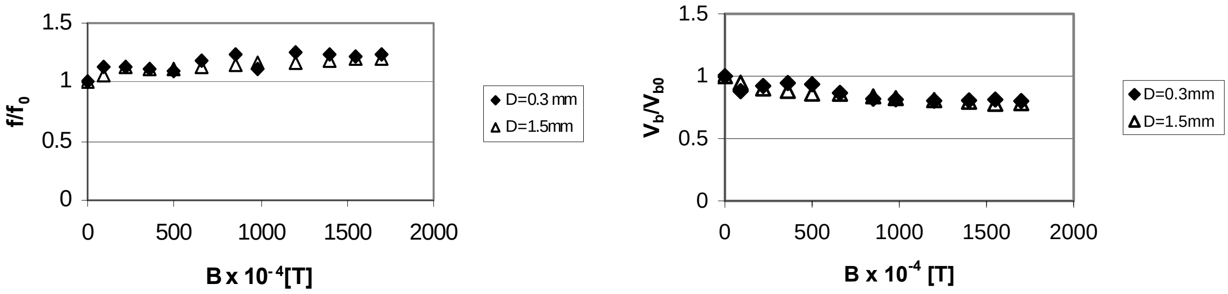
The comparison of the variation level of bubbles average frequency and average volume, when the field gradient is reversed ($\nabla B \| -\vec{g}$), for the injection hole D = 0.3 mm are presented in Figure 4 (a, b). The general pattern is similar – the bubbles average frequency decreases and the bubbles average volume increases with the applied magnetic field.

The comparison of the results for the two liquid samples shows that their magnetic properties have an important effect on the bubble frequency and average bubble volume as shown in Figure 5 (a, b). For the opposite case ($\nabla B \| -\vec{g}$), the influence of the sample saturation magnetization is less important.

As pointed out by H.J. Ivey [13], the ideal information to be derived from a nucleate boiling experiment regarding bubble frequency and volume would be the value of each individual bubble volume with its associated frequency (measured as the inverse of the bubble period) at the nucleation site.

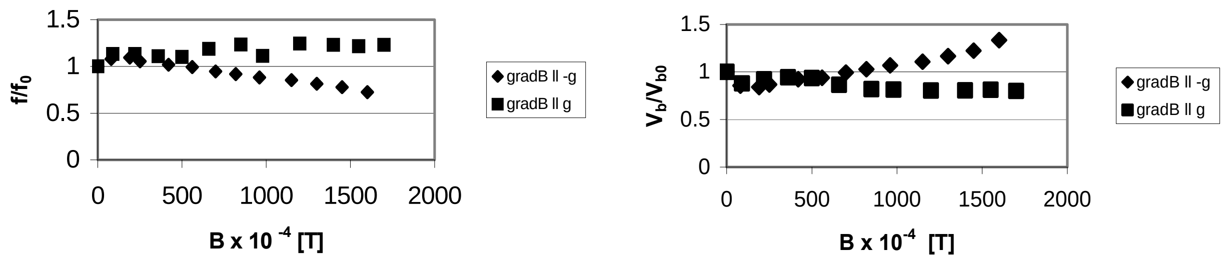
Applying this principle to our experiment in order to make a similarity with the nucleate boiling phenomenon, the relationship between the bubble frequency and volume for several values of the applied field was established. In order to obtain this relationship we used the recorded data as follows:

- the values of the associated frequency of individual bubbles as the inverse of the measured bubble period;
- the bubble volume as the product of average flow rate per bubble period and the bubble period;
- the equivalent bubble diameter, assuming the bubble shape as spherical.



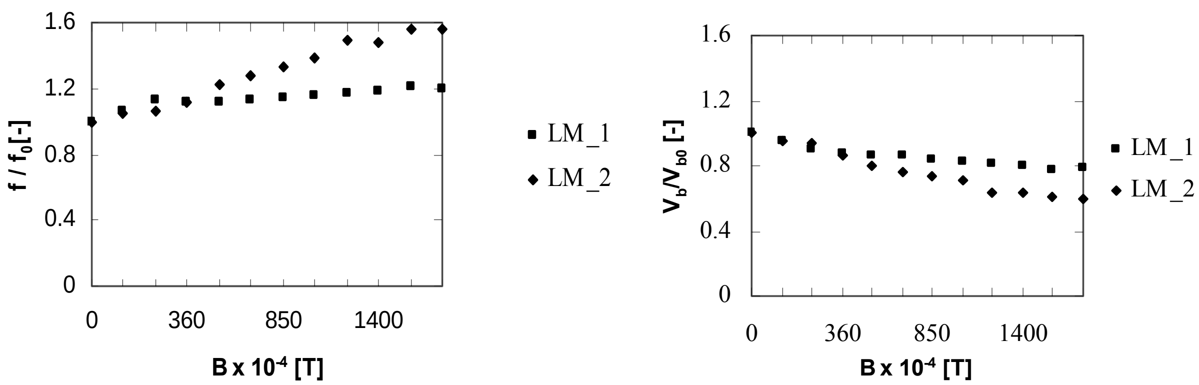
(a) (b)

Figure 3. Average bubbles frequency and volume versus the applied magnetic field with, $\nabla B \| \vec{g}$ magnetic liquid sample LM_1



(a) (b)

Figure 4. Average bubbles frequency and volume versus the applied magnetic field, liquid sample LM_1, injection hole D=0.3 mm



(a) (b)

Figure 5. Average bubbles frequency and volume versus the applied magnetic field with $\nabla B \| \vec{g}$, for the injection hole D = 1.5 mm

The results are presented in Figure 6 and show that in the absence of the magnetic field the dependence of bubble frequency and its equivalent bubble diameter is $f \propto D_{eq}^{-3}$, a case which corresponds to the transition region of the boiling theory, when the bubble dynamics is assumed to depend on buoyancy, drag and surface tension. Further, if a non-uniform magnetic field is applied, the exponent of D_{eq} changes with the value of the applied field – in this case decreases as the magnetic field intensity is increased.

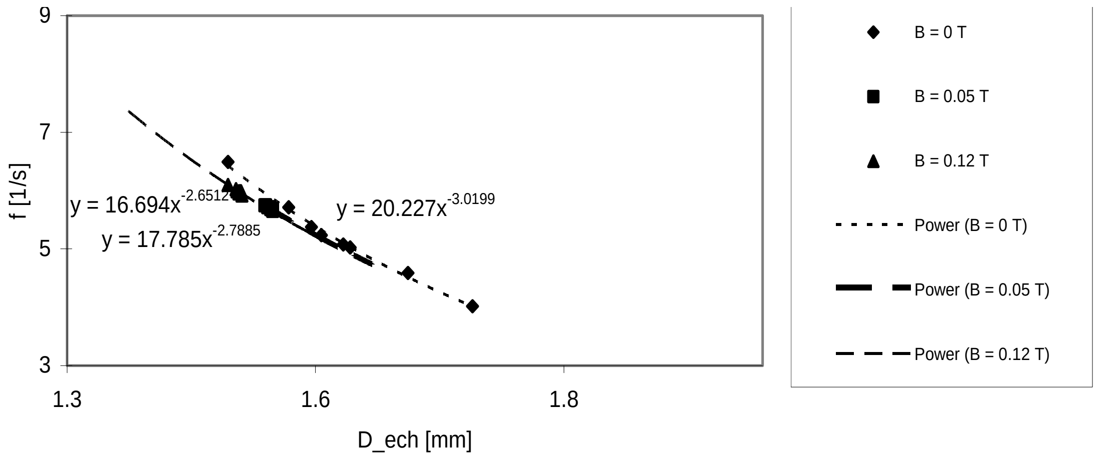


Figure 6. Comparison of bubble frequency as a function of bubble volume with different values of the applied magnetic field when $\nabla B \| \vec{g}$, (liquid sample LM_1, D = 1.5 mm)

4. CONCLUSIONS

The obtained results show the effect of the orientation of magnetic field gradient with respect to gravity on the bubble frequency and volume at departure as follows:

- for $\nabla B \| \vec{g}$, the bubble frequency increases while the average bubble volume decreases;
- for $\nabla B \| -\vec{g}$, the bubble frequency decreases while the bubble volume increases.

The effect is similar irrespective of the injection hole diameter. Moreover, it was proved that the value of saturation magnetization of the liquid sample has a major effect on the bubble frequency and average volume, when $\nabla B \| \vec{g}$.

An analysis of the dependence between individual bubble frequency and volume (or equivalent diameter) with the applied magnetic field (case $\nabla B \| \vec{g}$) was carried out. The results show that $f \propto D_{eq}^{-m}$, where the exponent m is depending on the value of the applied magnetic field.

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