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Magnetic liquid sensor for very low gas flow rate with magnetic flow adjusting possibility

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Abstract

A gas flow rate sensor which is based on the change of magnetic properties of magnetic fluid due to gas bubbles is well known. A vessel filled with magnetic fluid is equipped with an exciting coil and two detecting coils, the voltage difference between the coils, induced by bubbles, being a measure of the flow rate. This type of device does not permit simultaneously adjustment of the flow rate. This paper describes a new type of micro flow sensor, including the components of the experimental equipment used. The bubbling gas flow rate, i.e. the frequency of bubbles, was measured up to 20 Hz. Under the influence of a nonuniform or uniform magnetic field, due to first order magnetic levitation and magnetic pressure effects, supplementary forces of magnetic origin appear beside the gravitational one, which significantly modify bubble formation and emission frequency. Experimental data are presented concerning the characteristics of a model sensor illustrating the efficiency of magnetic adjustment of gas flow rate. © 1997 Elsevier Science S.A.

Keywords: Inductive transducers; Magnetic liquids; Gas flow rate; Magnetic flow adjustment

1. Introduction

Magnetic fluids are used as basic components of various sensors and transducers, e.g. for acceleration/inclination angle [1–3] and aerodynamic quantities (differential pressure, flow rate, velocity) [4,5]. Constructive details and characteristics of magnetofluid inductive flow rate sensors and flow meters are given in [6], including those of sensors for very low flow rate values (~ 1 l/h).

The change in magnetic properties of magnetic fluids due to gas bubbles is the origin of another type of micro gas flow sensor [7,8]. Such a sensor has an excitation coil and two search coils around a vertical magnetic fluid column. When gas bubbles enter the vessel from the central part, a difference of magnetic flux density is induced between the search coils and the gas flow rate is measured from the resulting voltage difference. Assuming spherical bubbles, the change in magnetic flux as a function of the bubble's position and radius was analyzed in [9]. It was shown that the flux change is proportional to the bubble volume, therefore the method is suitable for detecting very low gas flow rates. Note, however, that this type of device does not permit simultaneously adjustment of the flow rate. In this paper a new type of adjustable micro flow sensor is proposed whose principle of functioning and model, including the main components of the experimental equipment used, will be described in what follows.

2. Magnetic adjustment of bubbling gas flow rate

Let us consider a gas bubble of radius R in a magnetic fluid of magnetization $\vec{M}$ under the action of a uniform magnetic field of intensity $\vec{H}$. Taking into account the expression of the stress tensor of magnetic fluids in the quasi static condition, the generalized Laplace equation [10] for this particular case can be written in the form:

$$p_g - p_l = \frac{2\sigma}{R} + \frac{\mu_0 M_n^2}{2} \qquad (1)$$

where p_g is the pressure of gas in the bubble, p_l is the liquid pressure, σ is the surface tension, $p_m = \mu_0 M_n^2/2$ is the 'magnetic' pressure and $M_n = \vec{M} \cdot \vec{n}$ is the normal

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component of the magnetization vector, $\vec{n}$ being the unit vector normal to the gas–liquid interface.

Assuming that the gas is injected in the liquid through a cylindrical nozzle of internal diameter d_0, the minimum pressure difference necessary to form a gas bubble is given by Eq. (1) for $R = d_0/2$ [11], i.e. bubble formation is influenced by magnetic pressure.

The departure diameter D_d of gas bubbles formed at a submerged orifice, for relatively low flow rate, is determined by the equilibrium of buoyancy and surface tension forces [12]:

$$D_d = C(d_\theta, \theta)\left[\frac{\sigma}{g(\rho_l - \rho_g)}\right]^{1/2} \cong C(d_0, \theta)\left(\frac{\sigma}{\rho_l g}\right)^{1/2} \qquad (2)$$

where ρ_l is the liquid density, ρ_g is the gas density and g is the gravitational acceleration. In the above relation $C(d_0, \theta)$ is a coefficient depending on the internal diameter d_0 of the submerged orifice and on the solid–liquid contact angle, θ.

Suppose that the liquid is magnetizable and it is placed in a nonuniform magnetic field of gradient $\nabla H \| \vec{g}$. The resultant buoyancy force acting on a bubble of volume V_b, if the liquid magnetization and the field gradient may be considered constant within the liquid volume V_b expelled by the bubble, will be [10]

$$\vec{F}_a = -\rho_l \vec{g} V_b - \mu_0 M V_b \nabla H \qquad (3)$$

or

$$\vec{F}_a = -\rho_l \vec{g}_a V_b. \qquad (4)$$

Here

$$\vec{g}_a = \vec{g} + \frac{\mu_0 M}{\rho_l} \nabla H \qquad (5)$$

is the apparent acceleration whose second term, $(\mu_0 M/\rho_l)\nabla H$, is the 'magnetic' acceleration due to the first order levitation effect in magnetic fluids.

Consequently, the volume of departing bubbles from the nozzle submerged in magnetic liquid depends also on the applied field:

$$V_b = \frac{\pi}{6} C^3(d_0, \theta)\left(\frac{\sigma}{\rho_l |\vec{g} + (\mu_0 M/\rho_l)\nabla H|}\right)^{3/2} \qquad (6)$$

Relations (1) and (6) show that applying a magnetic field of adequate intensity and spatial configuration, bubble formation, departure diameter/volume and emission frequency can be influenced in a simple way, i.e. the bubbling gas flow rate is magnetically adjustable.

3. Experiment

In order to verify the above expectations concerning flow rate adjustment by magnetic field, the experimental set-up sketched in Fig. 1 was used. A finely tunable variable speed aerodynamic tunnel served as variable pressure source to generate air bubbles through a glass capillary submerged in a magnetic liquid of approx. 15 kA/m saturation magnetization. The sensing coils A and B with 530 turns each, have internal diameters of 9 mm. Their length of 2 mm was set comparable to the diameter of the bubbles.

For zero flow rate (no bubbles) the inductances of the coils are set to be equal, $L_1 = L_2$, while when a bubble is passing through one of the coils $L_1 \neq L_2$. The a.c. bridge gives a transient non zero voltage difference for each bubble, corresponding to $\Delta L = L_1 - L_2 \neq 0$. An electronic counter indicates the frequency of bubbles, proportional to the gas flow rate. At the greatest sensitivity the above described model sensor gives a countable signal for bubbles whose diameter is greater than 0.3 mm; the diameter of gas bubbles injected by the nozzle is in the range ≥ 1 mm, well above the sensitivity limit. The cylindrical vessel with magnetic liquid, sensing coils and gas injecting nozzle, is placed between the poles of an electromagnet, as indicated in Fig. 1. Cylindrical flat surface and hyperbolic pole pieces were used to obtain uniform, respectively constant gradient nonuniform magnetic fields in the working zone of the sensor.

The scope of these experiments was to show the efficiency of magnetic adjustment of gas flow rate through the sensor. For a certain pressure difference Δp there corresponds a frequency f of gas bubbles injected through the nozzle in the magnetic liquid at zero magnetic field. Applying a magnetic field of increasing intensity, the bubble frequency decreases and finally vanishes at a certain field value. The bubble frequency–magnetic field intensity curves for uniform and nonuni-

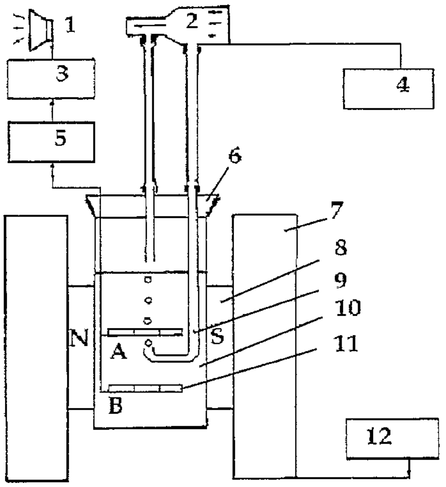

Fig. 1. The functioning principle of the gas flow sensor: 1, loudspeaker; 2, aerodynamic tunnel; 3, counter and sound generator; 4, stabilized a.c. power supply; 5, a.c. bridge; 6, rubber stopper; 7/8, coil/poles of electromagnet; 9, glass capillary; 10, magnetic fluid; 11, A/B coils of the sensor; 12, stabilized d.c. power supply.

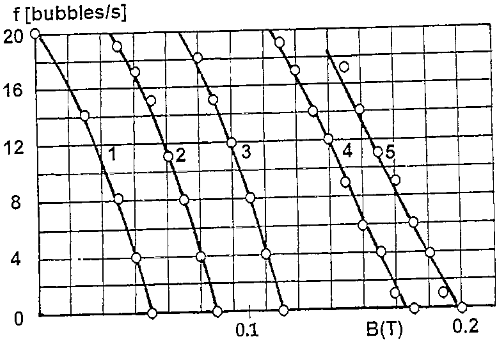

Fig. 2. Variation of emission frequency of gas bubbles with magnetic field induction B (plate pole faces, uniform field). **1** $\Delta P = 84$ mm H_2O, **2** $\Delta P = 96$ mm H_2O, **3** $\Delta P = 108$ mm H_2O, **4** $\Delta P = 136$ mm H_2O, **5** $\Delta P = 144$ mm H_2O.

form magnetic field configurations are given in Figs. 2 and 3 respectively.

The diagram presented in Fig. 2 shows that a relatively small change of the field intensity, that is, the corresponding variation of the magnetic pressure term in Eq. (6), produces a large variation of bubble frequency. As expected, the supplementary buoyancy force of magnetic origin corresponding to the magnetic acceleration term in Eq. (4), has an opposite influence and therefore the bubble frequency variation in nonuniform field is somewhat slower (Fig. 3), compared to the previous case.

4. Conclusions

The bubbling gas flow rate through a micro flow sensor with magnetic liquid can be adjusted applying a uniform or nonuniform magnetic field. The effect is due to the magnetic pressure term in the generalized Laplace equation and to the supplementary buoyancy force corresponding to the first order magnetofluid levitation force on bubbles in a nonuniform magnetic field. The experimental results show the efficiency of magnetic adjustment of bubbling gas flow rate through the flow sensor.

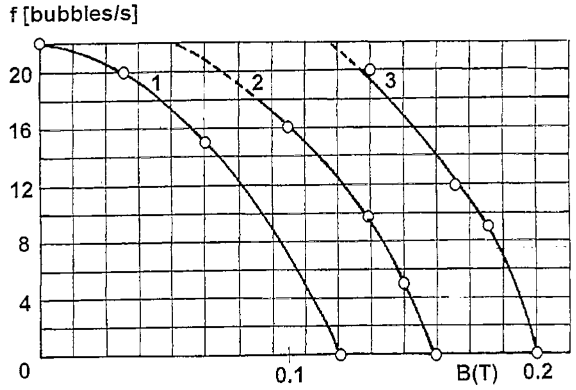

Fig. 3. Variation of emission frequency of gas bubbles with magnetic field induction B and its gradient G (hyperbolic pole faces). **1** $\Delta P = 104$ mm H_2O, $G = 1.18$ T/m, **2** $\Delta P = 116$ mm H_2O, $G = 1.69$ T/m, **3** $\Delta P = 132$ mm H_2O, $G = 2.0$ T/m.

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