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Detection and characterization of elongated bubbles and drops in two-phase flow using magnetic fields

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Abstract

We report a method to detect and to measure the size and velocity of elongated bubbles or drops in a dispersed two-phase flow. The difference of the magnetic susceptibilities between two phases causes a force on the interface between both phases when it is exposed to an external magnetic field. The force is measured with a state-of-the-art electromagnetic compensation balance. While the front and the back of the bubble pass the magnetic field, two peaks in the force signal appear, which can be used to calculate the velocity and geometry parameters of the bubble. We achieve a substantial advantage over other bubble detection techniques because this technique is contactless, non-invasive, independent of the electrical conductivity and can be applied to opaque or aggressive fluids. The measurements are performed in an inclined channel with air bubbles and paraffin oil drops in water. The bubble length is in the range of 0.1–0.25 m and the bubble velocity lies between 0.02–0.22 m s⁻¹. Furthermore we show that it is possible to apply this measurement principle for nondestructive testing (NDT) of diamagnetic and paramagnetic materials like metal, plastics or glass, provided that defects are in the range of 10⁻² m. This technique opens up new possibilities in industrial applications to measure two-phase flow parameters and in material testing.

Keywords: two-phase flow, bubble detection, slug flow, force measurement, non-destructive testing

(Some figures may appear in colour only in the online journal)
and mostly dependent on the electrical conductivity of at least one phase. Newer developments are based on the measurement of electrical conductivity or capacity but these are either dependent on the presence of electrical conductivity \([11, 12]\) or they are invasive \([13]\). Further non-invasive methods are acoustic detection \([14]\), Lorentz force velocimetry (LFV) \([15]\) or ultrasound techniques \([16]\).

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Nondestructive material testing (NDT) is an interdisciplinary field to test specimen for anomalies without destroying them. Those anomalies can be cracks, cavities or inclusions in material. Usually NDT is classified into three categories, which are visual, surface and volumetric methods \([17]\). Visual methods can be mirrors, endoscopes, optical microscopy or the naked eye. Lorentz force eddy current testing (LET) \([18]\), magnetic particle testing or thermography rank among the surface techniques, and acoustic, ultrasonic or radiography techniques to the volumetric methods. As in the flow measurement techniques most of these methods are dependent on optical accessibility, electrical conductivity or they need a direct contact to the specimen. By using magnetic fields it is possible to circumvent these limitations.

2. Theory

We report a technique which overcomes the restrictions of opacity, dependency on electrical conductivity and disturbance of the flow caused by invasive measurements \([19]\), patent pending). The principle of this technique is illustrated in figures 1(a) and (b). A single air bubble is entrapped in a test section of a channel which can be inclined. Due to buoyancy the bubble accelerates and streams under the top plate of the test section. This simple two-phase flow is exposed to a localized magnetic field, provided by a permanent magnet. Because the two phases have a different magnetic permeability \(\mu\), the field lines deform in the direction of the medium with a higher magnetic permeability. Due to this deformation, a force acts on the interface between the phases. This force is described by equation (1), which is derived from the Helmholtz formula \([20]\)

\[
\vec{F} = - \int \frac{1}{2} \mu_0 \mu_2 \nabla \mu \, dV. \tag{1}
\]

Here \(\vec{F}\) is the magnetic field strength and \(V\) the volume. The force \(\vec{F}\) is effective in the area where \(\mu\) changes. Assuming that \(\nabla \mu\) is concentrated on the rim of the bubble we define:

\[
\nabla \mu = (\mu_2 - \mu_1) \delta_S (\vec{r}) \vec{n}. \tag{2}
\]

Where \(\mu_2\) is the magnetic permeability of water and \(\mu_1\) the magnetic permeability of air. The function \(\delta_S\) is centered on the interface and \(\vec{n}\) denotes the surface normal vector. Furthermore with the relation between the magnetic flux density \(B\) and the magnetic field strength \(\mu_2 H\) (because \(\chi \ll 1\) and with \(\mu_2 - \mu_1 = \mu_0 (\chi_2 - \chi_1)\)) which is the relation between the magnetic permeability and the magnetic susceptibility, it is possible to calculate the force which acts on the interface \(A\) between the two media.

\[
\vec{F} = - \int \frac{1}{2} \mu_0 \nabla (\chi_2 - \chi_1) \, dA \, \vec{n}. \tag{3}
\]

Due to equation (3) the magnetic force \(\vec{F}\) depends on the square of the applied magnetic induction \(B\), the difference between the magnetic susceptibility of the two phases \(\Delta \chi = (\chi_2 - \chi_1)\) and the permeability of free space \(\mu_0\). In the case of the elongated bubble, two square wave signals are measured. The first appears when the bubble enters the magnetic field and the second peak appears when the bubbles leaves the magnetic field. The magnitude of the peak is dependent on the area of the bubble’s front or back. As a start we assume the rounded bubble front or back as rectangular, because the bubble is well confined by the width \(b\) of the test section. Furthermore we neglect the stray field and assume a stepped magnetic field distribution. The area \(A\) is defined by the product of \(b\) and bubble height \(h_b\). This simplification leads to a theoretical, normalized square wave force signal shown in figure 2.

\[
F_1 = - \frac{1}{2} h_b \, b \, \frac{\mu_0}{\mu_2} (\chi_2 - \chi_1). \tag{4}
\]

When the bubble enters the magnetic field the force acts on the front side of the bubble. Because air is paramagnetic, its magnetic susceptibility is higher than that of the diamagnetic water. Therefore the field lines deform in the direction of the air (figure 1(a)). The difference of the magnetic susceptibilities is negative and the force on the bubble becomes positive. Because of Newton’s third law the opposite force acts on the magnets. This drag force is oriented in the opposite direction and, as a result, a negative force will be measured which lasts as long as the bubble front is located in the magnetic field. In the second case, when the bubble leaves the magnetic field, the field lines also deform in the direction of the air, but in the positive \(x\)-direction. Consequently the resulting drag force on the magnets is positive. If the bubble extends across the whole magnetic field the force is zero. Because only the force in the \(x\)-direction is measured, the water-plastics interface between the fluid and the channel, which is made of polycarbonate, and the air-water interface don’t affect the measurement. These interfaces cause force components in the \(y\)-direction. With the time markers and the knowledge about the spatial distribution of the magnetic field it is possible to calculate the velocity and length of the bubble (see section 4).

This principle works for every combination of media as long as their magnetic susceptibility is different. In this way the detection of solid particles in liquids or gases and the detection of inclusions and defects in solid bodies is conceivable. In this paper we focus on air/water slug flows which are simpler to measure because the bubbles are longer than the inner channel dimensions \([21]\). Slug flow is present in industrial processes which opens new fields of applications for this technique. The application to immiscible liquid–liquid flow (water/oil), which can occur in pipelines, is possible as well. This is more challenging because the difference of the magnetic susceptibility in comparison to air/water is one order smaller. Furthermore we show results of solid body measurements which are directed towards material testing.
Experimental setup

The experimental setup is arranged to perform experiments with air bubbles of different heights, lengths and velocities. The investigations are conducted at a 1.50 m long test section which is part of a water channel [22] but here dismounted and closed at both ends. The inner cross section is quadratic (50 \times 50 \text{ mm}^2). The channel is made of polycarbonate which enables the application of an optical measurement technique. Via two tubes it is possible to set the volume of air or paraffin oil inside the test section accurately with the help of a syringe. Tap water is used as continuous phase. One end of the channel is fixed and the other end can be raised by a linear guide unit. The working principle is like a spirit level and inclinations up to 1.15° can be adjusted. Because of the sensitive linear guide unit it is possible to set different bubble velocities by varying the inclination. The position of rest is −0.4° to ensure that the bubble flows back to the starting position.

Two permanent magnet systems are used to provide the magnetic field. NdFeB magnets are used to provide the magnetic field. These are currently the strongest available permanent magnets, which have a magnetic flux density of about 0.5 T near the surface of the magnet. The classic magnet system (figure 3(a)) consists of 2 × 2 opposing cubic magnets with a side length of 30 mm. Both pairs are connected by a yoke made of carbon-fiber-reinforced carbon. The second magnet system is a Halbach system (figure 3(b)) [23]. This is a special composition of magnets to reduce the stray field and consequently increase the magnetic flux density between the two arrays. One array consists of 5 single bar magnets whose magnetizations are oriented at angles of 90 degrees to each other. This results in three alternating magnetic flux spots in the test section. For both systems the distance of the magnets is designed in such a way that the magnets are close (~1 mm) to the channel to ensure the highest possible magnetic flux density of about 0.21 T.

The force measurements are performed with an electromagnetic force compensation (EMFC) balance [24–26], which is a state-of-the-art monolithic weighing cell. To measure the horizontal drag forces the EMFC balance is arranged at an angle of 90 degrees in comparison to the normal case of application. Normally this weighing cell is constructed for gravimetric analysis. A linear voice coil actuator is used to balance the proportional lever arm by the method of electromagnetic compensation. The sampling frequency of the balance is 30 Hz and the force resolution is \( \leq 1 \text{ \mu N} \). Both magnet systems can be mounted with an aluminum attachment on the EMFC balance. For the Halbach array measurements, a second balance with a dummy made of copper is used to filter background noise in the force signal. Because the dummy has the same weight like the magnet system, it is possible to increase the resolution to 0.02 \text{ \mu N} with the differential force measurement method. This method plays an important part in measuring very small forces which occur when the magnetic susceptibilities of the two phases are nearly equivalent like in oil/water measurements.

All measured bubbles span the width of the test section, which is \( b = 50 \text{ mm} \) (figure 1(b)). The bubble is recorded with an industrial CCD camera from below and from the side at up to 17 frames per second. To synchronize the position of the bubble with the force signal an LED is used. The bubble front is defined as the foremost point (see white crosses in figures 4(a) and (b)) and the back of the bubble as the rearmost.
These points can be tracked by evaluating the single frames of the recording with the Matlab function ‘ginput’. Shortly before the bubble enters the field of view of the camera the LED flashes up and the time is marked as the start time \((t = 0)\) in the force signal. Similarly a space-time diagram for the bubble is possible and can be compared with the force signal.

By adjusting gas volume and bubble velocity it is possible to get different heights of the bubble because the bubble front is more blunted for higher velocities (figure 4(b)) and the air will be dammed up. An insignificant laminar backflow of the water \((v = 0.01 \text{ m s}^{-1}, \text{Reynolds number: } \text{Re} = \frac{v l}{\nu} = 500, \text{where } \nu \text{ is the kinematic viscosity})\) when the bubble is passing the magnetic field could be measured with particle image velocimetry (PIV). The resulting Lorentz forces \([27]\) on the magnet system can be neglected because the product of electrical conductivity and flow velocity is lower than the limit of detection. With the data given in \([28]\), we can estimate a Lorentz force of 1.65 nN for the velocity \(v = 0.01 \text{ m s}^{-1}\) and the electrical conductivity \(\sigma = 0.035 \text{ S m}^{-1}\) of tap water. We define the flow as slug flow with reference to the definitions in \([21]\). The difference of the magnetic susceptibility between water and air is \(\Delta \chi = 9.4 \cdot 10^{-6} \,[29]\).

In a second approach we have extended the measurements to solid bodies (figure 5). For these measurements, the test section is dismounted and the solids are moved quasi-statically through the magnetic field (classic magnet system). The positions of the solids can be tracked with the help of scale paper. By this means it is possible to determine the entry and the exit of the solid bodies and the defects accurately to the millimeter. Here the cube edge is defined as \(x = 0\) mm. To provide the highest possible magnetic field, the solids are located off-centre in the immediate vicinity (<1 mm) of one magnet. Near the magnet surface the magnetic flux density is about 0.5 T. Aluminum bars with different lengths and a cross section of...
between air and aluminum is $\Delta \chi = -21.1 \cdot 10^{-6}$ [29]. To show that this technique could be suitable for NDT applications, specimens made of glass and polycarbonate with a hole of 10 mm diameter were tested. This is a typical size of shrink holes or nonmetallic inclusions, which can appear in casting [30, 31]. Furthermore in ceramic matrix composites (CMCs) cracks or crack fields can have dimensions in the order of $10^{-2}$ m [32] and in further composite material like fiber reinforced plastics voids can occur with diameters up to 10 mm [33].

4. Measurement results and discussion

In this section, we present a collection of bubble, drop, solid body and NDT measurements. Figure 6(a) shows a typical force signal while a bubble passes the magnet system. The two green dashed lines indicate when the bubble front enters or leaves the magnet system and the red dashed lines indicate the same for the back of the bubble. Because there is a small magnetic stray field, the signal is not rectangular anymore and there is already a force before the first green marker. The second green marker is also shifted relative to the peak because of the stray field, but calculations in the next sections show that this has no essential influence on the measurement uncertainty. As explained in the theory, the first peak is negative because the permeability of air is higher than that of water. The second peak is positive because the magnetic field lines deform in the direction of the bubble and the acting force drags the magnet system in the positive $x$-direction. Although mostly there is a small reduction of the height of the bubble between the front and the back (indicated in figure 1(b)), the force between the two peaks is zero. We have observed a symmetric shape of the bubble when it is at rest or has a low velocity. At higher inclinations and velocities the bubbles become asymmetric for reasons described in [34].

Figure 6(b) indicates three force signals for bubbles of the same length at different velocities. The faster the bubble passes the magnets the narrower is the signal. This fact shows the difficulty of measuring bubbles with high velocity because of limited time resolution. The front of the bubble becomes blunted which decreases the influence of the rounded bubble shape, but the back of the bubble is not flat at high velocities in some cases. This can result in a small further peak (blue signal) between the two main peaks. The reason why the magnitude of the second main peak is usually less than the first one is that the back of the bubble has a smaller height. Here the bubble fronts have roughly the same height. A further feature is that the second peak of the red signal is narrower than the first, because the bubble is slightly accelerating. This complicates the calculation of the bubble length, which will be described below. Hence, we use the average velocity for both peaks to decrease the measurement uncertainty. In addition, the uniform acceleration can be calculated using the two velocities and the time difference between the maxima of the peaks.

The bubble velocity is calculated by using the two force peaks (figure 6(a)) which occur when the bubble front or back passes the magnetic field. The velocities result from the time intervals $\Delta t_1$ and $\Delta t_2$ divided by the side length $l_m$ of the cubic magnets. Figure 7(a) shows the linear dependency of the bubble velocity measured with the help of the force peak and the velocity measured by camera. For the reference measurement, we track the bubble on single pictures of a video. Here 72 velocities are measured (36 bubbles). We have plotted a linear fit to the measurement points, which has the equation $v_{\text{force}} = m \cdot v_{\text{camera}} + n$. Here $m$ is the slope and $n$ is the offset. The slope is $m = 0.98$ and there is practically no offset ($n = 0.0007$ m s$^{-1}$). The coefficient of determination is $R^2 = 0.98$. This shows the good agreement of the velocities obtained from the force measurements and the velocities measured with the camera. The experimental data show a stronger deviation when the bubble velocity increases. These deviations could be explained with the camera measurements, which become more inaccurate because fewer pictures can be recorded during the transit time of the bubble. The histogram in figure 7(b) shows the relative error of the measurement. The standard deviation is 0.089.

The bubble length is calculated with the product of the time span between the two peaks $\Delta t_3$ and the already obtained bubble velocity $v_b$. By using the two peaks, an average velocity of the bubble is calculated. This procedure helps to
correct the influence of a uniform acceleration of the bubble, which is more influential for small bubble velocities. For higher velocities we assume that the bubble velocity is constant in the area of the magnetic field. However, figure 8(a) shows a linear behaviour of the bubble length between the force method and the camera measurements. Even though the linear fit shows an offset ($n = 9.88$ mm) and the slope differs more from 1 ($m = 0.86$), the coefficient of determination of $R^2 = 0.96$ confirms a reasonable degree of linearity. Because the slope is smaller than 1, there is a negative shift of the relative error, which means that the lengths obtained from the force measurements are mostly smaller than the camera measurements. This results in a slight shift of the distribution in the positive $x$-direction (figure 8(b)). The standard deviation is 0.062. Of course, the measurement uncertainty of the velocity measurement propagates and has a direct influence on the length measurement, which is a main reason for the shown deviations. Furthermore, the acceleration of the bubble increases the error.

The dependence of the absolute value of the force peak on the bubble height is shown in figure 9. The magnet system used is the Halbach array because the magnetic field distribution of this is well studied and necessary for an accurate calculation of the expected forces [35]. An averaged magnetic flux density of $B = 0.21$ T is assumed for the top region of the magnets, i.e. the area of the upper 10 mm between the two arrays of the Halbach system, where the bubbles pass the magnet system. According to equation (4), the dependence of the force on the bubble height is linear, which can be confirmed by experimental data. The limits for the measurement of the length, velocity and height of the bubble are determined by the current experimental setup. Because a 30 mm cubic magnet is used, the bubbles have to be larger than 30 mm in
length. This can be improved by using a much smaller magnet. It is not necessary to have a minimum velocity of the bubble. Currently the upper limit is about 0.25 m s$^{-1}$ which, of course, depends on the bubble length. The theoretical bubble height of the slugs could be one order smaller than the here investigated 4 mm, but this is impracticable with the current setup.

Figure 10(a) shows the force signal while a paraffin oil drop is passing through the magnet system. Here the Halbach array is used to resolve the forces, which are less than 10 $\mu$N. The difference of the magnetic susceptibility between water and paraffin oil is very small ($\Delta \chi = -2.03 \cdot 10^{-7}$ [36]). The characteristic of the force signal is the same as in the air bubble measurements, but in addition there are some bumps in the force signal, which are related to the alternating magnetic flux spots which occur at the Halbach array.

The measurements were extended to solid bodies. A paramagnetic aluminum bar of 100 mm length is moved quasi-statically through the magnetic field (figure 10(b)). This is a static measurement because a velocity would additionally cause Lorentz forces. The indicators where the bar enters or leaves the magnet system are slightly shifted, which could originate from the off-centre movement through the magnet system. Because the difference of the magnetic susceptibility is negative like the combination water/air, the first peak is negative as well. The high magnetic flux density causes forces up to $\pm 800 \mu$N. We have expected a rough square-wave signal like in figure 2, because the front and the back of the solid body are flat. We can conclude that the influence of the stray field and the inhomogeneous distribution of the magnetic field $B$ on this measurement technique is higher than the rounded shape of a real bubble.

Further specimen were tested with regard to nondestructive testing (NDT). Figures 11(a) and (b) show force signals which occur when a defect in a glass or polycarbonate specimen (10 mm hole, see figure 5) passes the magnet system. Because the defect is smaller than the cubic magnets, there is no range between the two force peaks where the force is zero. We can conclude that the measurement resolution is directly dependent on the size of the magnet. Otherwise we could calculate the dimensions of the defect. If a smaller magnet is used, the length calculation could be very precise because there is no need to calculate the velocity beforehand. But a smaller cubic magnet would also affect the measurement resolution negatively due to a decrease of the magnetic field. It is conceivable to use magnet systems, which have smaller spatial dimensions but have an optimized magnetic field, to measure smaller defects [37]. However, these figures do not raise a claim for the precise measurement of the hole. They prove that this technique could be used for NDT applications. It is conceivable to improve the procedure by scanning the specimen in all space coordinates. The increasing force signal is then an allusion to interfaces and a measurement even for geometrical complex defects is possible. Similar NDT applications are currently in development where attractive
and repulsive magnetic forces are measured with the help of capacity sensors [38].

5. Conclusions and outlook

We have investigated velocity and geometry of moving single bubbles and solid bodies with force measurements in combination with an external magnetic field. This contactless technique is based on the effect wherein forces act on an interface between two media with different magnetic susceptibilities. Due to the fact that the forces act on an interface it could affect the shape of the bubble. However, the forces are very small and consequently the intrusiveness of this method is negligible. By extensive measurements we have analyzed the velocity and geometry parameters of the bubble and compared the results with those of image evaluation. Air bubble heights between 4 and 14 mm and lengths between 100 and 225 mm were investigated and the velocities of the bubbles were in the range of 0.02–0.22 m s⁻¹. The velocities calculated with the help of the force method are in good agreement (+0.01 m s⁻¹) with the measured velocities of the reference method and show high linearity. The length measurements show higher deviations (+0.008 m) but are still reasonably accurate for this new method. Also paraffin oil drops were investigated and show that this effect can be applied to immiscible liquid–liquid flow. We have shown that the spherical shape of the bubble front and the neglect of the stray field of the magnets have little influence on the results. However, with a precise knowledge of the magnetic field distribution and the possible application of superconducting bulk magnets to increase the magnetic flux density, an increase of the measurement accuracy is feasible. The measurement resolution could be increased by using smaller magnets and magnet systems like cylindrical Halbach arrays, and a reduction of the distance between magnet and specimen, which could be the focus of future work. Until now the temporal resolution is much smaller in comparison with other flow measurement techniques and NDT-methods. Furthermore, after we have shown that LFV is insensitive to different velocity profiles [27, 28], the combination of both would enable the velocity measurement of both phases. In addition, the calculation of the volume fractions of both phases and the slip ratio between them is possible. The measurement of solid bodies, which shows similar characteristics in the force signal, extends this method with regard to NDT. In contrast to other techniques the contactless detection of defects even in diamagnetic and paramagnetic materials like plastics, glass or ceramics is possible. We attribute a high potential for industrial application to this method in the area of flow measurement technique and material testing.

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