SFB 609

Sonderforschungsbereich 609
Elektromagnetische Strömungsbeeinflussung in Metallurgie, Kristallzüchtung und Elektrochemie

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SFB-Preprint SFB609-10-2004

TECHNISCHE UNIVERSITÄT DRESDEN

Preprint Reihe
SFB 609

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Dresden, April 2004

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5th International Conference on Multiphase Flow, ICMF'04
Yokohama, Japan, May 30–June 4, 2004
Paper No. 260

Gas and liquid velocity measurements in bubble chain driven two-phase flow by means of UDV and LDA

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Abstract In the present paper the Ultrasonic Doppler Velocimetry (UDV) was validated for its capability to measure both gas and liquid velocities in transparent as well as opaque two-phase flows. Single bubbles rising in water, glycerin and the eutectic alloy GaInSn were studied using UDV. The obtained data with respect to the terminal bubble velocity are in good agreement with results known from the literature. Parallel measurements by means of Laser Doppler Anemometry (LDA) and UDV were performed in a further experiment in glycerin at higher gas flow rates leading to a formation of a bubble chain. The comparison of both methods demonstrated a good agreement. A special threshold method is tested successfully for data processing at UDV measurements in a bubble chain driven flow. First preliminary results showing the influence of a D.C. magnetic field on the drag coefficient and the wake of a bubble rising in a liquid metal are presented.

1. Introduction

Bubble driven flows have found wide applications in industrial technologies. In metallurgical processes gas bubbles are injected into a bulk liquid metal to drive the liquid into motion, to homogenize the physical and chemical properties of the melt or to refine the melt. For such gas-liquid metal two-phase flows, external magnetic fields might provide a possibility to control the bubble motion in a contactless way.

Numerous experimental and theoretical studies have been carried out on the movement of bubbles in transparent liquids [1-6], especially in water, also reviewed by Magnaudet and Eames [7]. The number of publications dealing with gas bubbles rising in liquid metals is comparatively small. The shortage of suitable measuring techniques can be considered as one reason for the slow progress in the investigations of gas-liquid metal flows. Powerful optical methods are obviously not available for measurements in liquid metals. The majority of measurements in liquid metal two-phase flows published until now was obtained using local conductivity probes [8, 9], hot wire anemometer [10] or optical fiber probes [11] to determine quantities such as void fraction, bubble and liquid velocity or the bubble size. However, measurements with any local probe disturb the flow in a significant way, especially if the structures to be investigated reach dimensions comparable to the probes. Diversions of bubble trajectories can be observed in the vicinity of a local probe. Bubble velocities and shapes are strongly affected in the moment if it hits the sensor. For these reasons the availability of non-intrusive techniques becomes important. In the case of opaque liquids the application of acoustic or ultrasonic sensors offers a possibility to get information about the flow structure and bubble quantities.

Andreini et al. [12] detected the noises generated by the bubbles releasing from the orifice by means of an acoustic microphone attached to a brass seal. In this way the authors were able to determine the bubble formation frequency in tin and lead and consequently the equivalent bubble diameter. Simultaneous measurements of bubble and liquid velocity can be realized using the ultrasonic Doppler velocimetry (UDV). First measurements by means of UDV in bubbly flows have already been published [13, 14], however, a number of questions with respect to the capabilities and limitations of UDV application in two-phase flows remains.

The perspective subject of interest for our work is the influence of external magnetic fields on the motion of gas bubbles in a liquid metal. UDV will be used to measure the velocity of a rising bubble as well as the liquid flow around the bubble. This paper is focussed on the reliability of UDV in case of velocity measurements in two-phase flows. In a first step the case of a solid sphere settling under gravity in glycerin was considered (section 3.1). Section 3.2 is dedicated to the rise of singular Argon bubbles in stagnant water, glycerin and GaInSn, respectively. Section 3.3 shows measurements performed in glycerin at higher gas flow rates where the bubbles form a rising chain. Here, we present a comparison between UDV and LDA measurements performed in parallel for reasons of validation. Preliminary results obtained in the eutectic alloy GaInSn with a D.C. magnetic field will be shown in section 3.4.

2. Measuring technique

During the last 20 years the Ultrasonic Doppler Velocimetry (UDV) became a powerful technique for flow velocity measurements in fluid engineering [15]. The method is based on the pulsed echo technique. Ultrasound pulses of few cycles are emitted from the transducer along the measuring line. The echo reflected from microparticles suspended in the liquid are received from the same transducer. The complete information of a velocity profile is contained in the echo. If the sound velocity of the liquid is known the spatial position along the measuring line can be determined from the time delay between the burst emission and its reception. The movement of an ensemble of scattering particles inside the measuring volume will result in a small time shift of the signal structure between two consecutive bursts. The velocity is obtained from a correlation analysis incorporating several consecutive bursts.

The measuring principle provides some advantages making the UDV technique very attractive for velocity measurements in liquid metal flows. UDV can be successfully used in opaque fluids such as liquid metals [16-19]. Specific problems of such applications with respect to measurements at high temperatures, the acoustic coupling or the availability of suitable reflecting particles have been discussed in detail in [18-20]. Moreover, spatiotemporal information can be obtained without prior knowledge of the flow structure. The capability to deliver instantaneously a full velocity profile provides a good basis for flow mapping. Flow mapping with pointwise measuring methods is often considered to be inefficient because it is very time consuming.

The DOP2000 velocimeter (model 2125, Signal Processing SA) with a standard 4MHz transducer (TR0405LS) was used to carry out the velocity measurements. The spatial resolution of the measurements is essentially controlled by the sound velocity of the liquid, the frequency of the ultrasonic bursts and the size of the piezoelectric element [21]. The measuring volume can be considered as a disc with axis on the measuring line. Because of the divergence of the ultrasonic beam the size of the measuring volume in lateral direction is not constant along the measuring line. Sound velocities of the different liquids considered in this study and the resulting size of the measuring volumes using the TR0405LS transducer can be found in Table 1. Values of the sound velocities for water and glycerin were taken from [21], whereas the sound velocity of GaInSn was determined by ourselves.

	water	85% glycerin	GaInSn
Sound velocity (m/s)	1480	1904	2650
Size of the measuring volume along the measuring line (mm) (burst of 4 cycles)	0.74	0.95	1.37
Size of the measuring volume in lateral direction (mm) at a distance of 100mm from the transducer	5.7	7.3	10.5

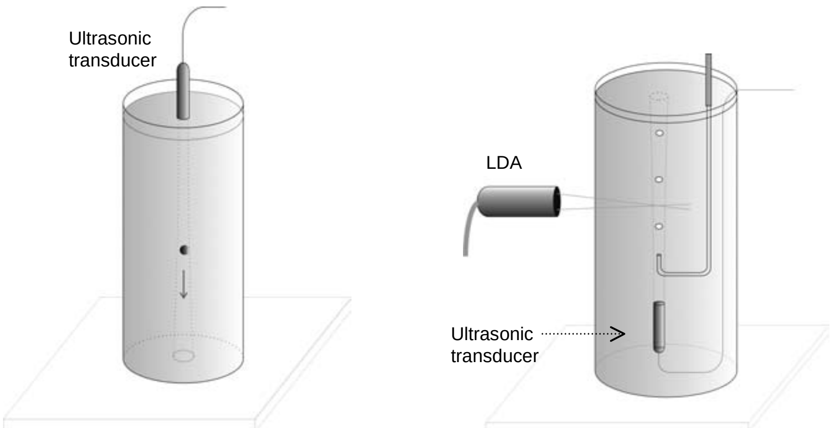
Table 1: Sound velocities and dimensions of the UDV measuring volume for water, glycerin and GaInSn

3. Experimental set-up and results

3.1 Solid steel sphere settling in glycerin

The Ultrasonic Doppler method has already been applied by Mordant and Pinton [22] to measure the velocity of a solid sphere settling under gravity in a stagnant fluid. This problem of a single moving solid body appears as a good test case and starting point for our activities in order to analyze and to understand the typical structure of the obtained velocity profiles. Furthermore, the drag coefficients were deduced from the measurements and compared with the standard drag curve [23] in order to check the reliability of our technique.

The experimental arrangement is shown in Figure 1(a). 85% glycerin solvent was used as liquid stored inside a cylindrical container made from Perspex with a diameter of 0.125m and height of 0.3m. The spheres were made from steel with diameters ranging from 2.0 to 7.5mm. The 4MHz ultrasonic transducer was positioned at the free surface parallel to the cylinder axis. Using this configuration the vertical velocity component along the cylinder axis can be determined. Solid spheres with different diameters were released directly below the transducer allowing us to observe simultaneously the settling velocity of the sphere as well as the wake until the sphere has reached the cylinder bottom.



(a) Sphere experiments (b) Gas-liquid two-phase flow experiments

Figure 1. Arrangements for experiments with solid spheres and rising bubbles, respectively

Figure 2 shows a snapshot of a typical velocity profile acquired by UDV. A sharp velocity peak is visible, which can be identified with the sphere motion. The region behind the peak showing a gradually decaying velocity illustrates the wake induced by the sphere. In front of the sphere the velocity of the stagnant liquid is found to be zero except a region closely in front of the peak. Here, some randomly distributed noisy peaks can be detected. These peaks are caused by artifacts due to multiple echo signals from different positions at the surface of the sphere. For spheres with different diameters similar velocity profiles were found, showing only certain quantitative variations in the height of the velocity peak, the signal magnitudes in the wake region or decaying times of the velocity in the wake.

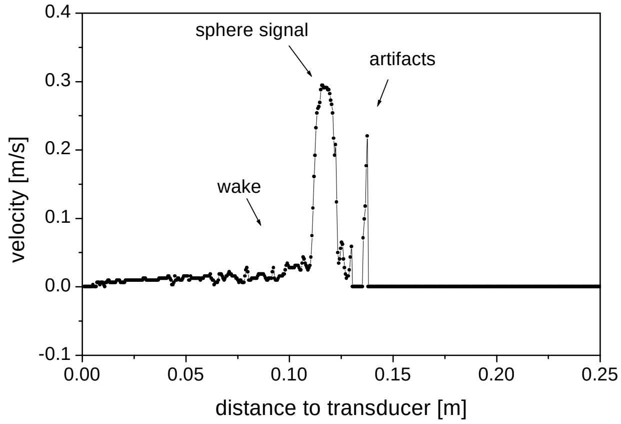


Figure 2. A snapshot of a typical UDV velocity profile for a solid sphere settling down in glycerin

Taking the maximum value at the velocity peaks as sphere velocity u_T, the drag coefficients C_D of the steel spheres were determined according to the following equation:

$$C_D = \frac{4}{3}\frac{(\rho_p - \rho) d_p g}{u_T^2 \rho} \tag{1}$$

where • $_p$ and d_p is the sphere density and diameter respectively, and • is the density of the liquid. These results reveal a good agreement with the standard C_D-Re curve of a sphere as shown in Figure 3. Therefore, the capability of the UDV technique to investigate the motion of spherical bodies in liquids and the resulting flow structure in the surrounding liquid is demonstrated convincingly.

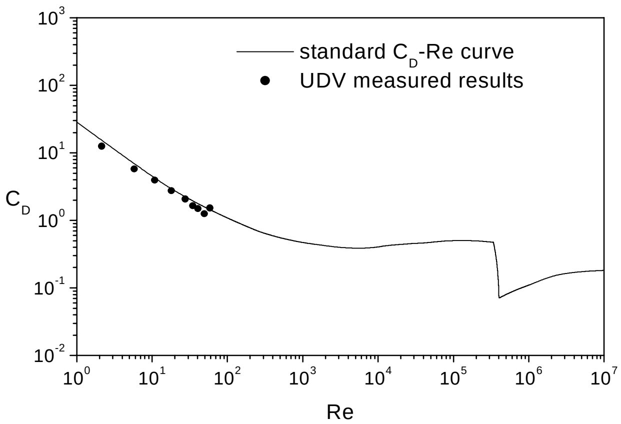


Figure 3. Comparison of UDV measured results to the standard drag curve of a sphere

3.2 Single bubbles rising in a liquid column

Bubble rising velocity measurements were conducted in tap water, 85% glycerin, and the eutectic alloy GaInSn. The material properties of these liquids and corresponding non-dimensional parameters can be found in Table 2. The experimental configuration is similar to that in the solid sphere experiment, a sketch of the set-up is displayed in Figure 1(b). The gas bubbles were injected into the liquids through a single orifice made from stainless steel with an outer diameter of 3mm. Different orifices were used to vary the inner diameter between 0.3mm and 1.5mm. The gas flow rate was controlled by means of a mass flow controller (MKS 1359C, MKS Instruments). It was kept extremely low in the range 0.005-0.02 cm^3/s in order to guarantee a single bubble regime. This resulted in intervals of about 15s between two consecutive bubbles. The UDV measurements showed us that the wake of a bubble was totally decayed during this time. Therefore, an influence on the bubble motion caused by the preceding bubble can be neglected.

	water	glycerin	GaInSn
Density ρ (kg/m^3)	998	1220	6361
Dynamic viscosity μ (kg/m·s)	9.8e-4	0.129	2.2e-3
Surface tension σ (N/m)	0.073	0.064	0.533
Morton number Mo	2.4e-11	8.5e-3	2.2e-13
Eotvos number Eo	2.8	5.3	3.4
Weber number We	4.7	1.3	2.8
Reynolds number Re	1360	6	3260

Table 2. Physical properties of the working liquids, and typical values of non-dimensional parameters defined by: $Mo = \frac{\mu^4 g}{\rho\sigma^3}$, $Eo = \frac{\rho g d_e^{\,2}}{\sigma}$, $We = \frac{\rho u_T^{\,2} d_e}{\sigma}$, $Re = \frac{u_T d_e}{\nu}$, (calculated for the equivalent bubble diameter $d_e = 5mm$)

The ultrasonic transducer was installed behind the nozzle inside the liquid or at the bottom wall of the cylinder, respectively. The ultrasonic beam was directed vertically along the bubble path. The recorded velocity profiles look very similar as compared to the case of the solid sphere. Because of the large difference in the acoustic impedance between the liquid and the gas phase the gas/liquid interface can be considered as ideal reflector of the ultrasound. Strictly spoken, the measured peak velocity which is taken as bubble velocity represents the vertical velocity component of the rear interface of the bubble being faced towards the ultrasonic transducer.

The equivalent bubble diameter d_e was estimated taking into account the injected gas volume V during a distinct time period and the number of bubbles n generated in the same interval according to the following equation

$$d_e = \left(\frac{V}{n}\cdot\frac{6}{\pi}\right)^{\frac{1}{3}} \qquad (2)$$

For large fluid containers, an estimation for the ratio of vertical to horizontal bubble perimeter E is given by the relation [23]

$$E = 1 / (1 + 0.163 \cdot Eo^{0.757}) \qquad Eo < 40,\ Mo \leq 10^{-6} \qquad (3)$$

Taking into account the values of the Eo number given in Table 2 results in perimeter ratio of 0.74

for water and 0.7 for GaInSn, respectively. Therefore, it can be expected that bubbles injected into both liquids will have an ellipsoidal shape.

Figure 4 displays the obtained bubble terminal rising velocities u_T as a function of the equivalent bubble diameter d_e. We compare our findings with curves fitted from experimental results reported by Haberman and Morton [1] and Kubota [2] for water and glycerin, respectively. Corresponding data for GaInSn are not available in the literature until now. We can note a sufficient agreement, although our data do not exactly match these curves. It is known from the literature, that the published data for the terminal velocity of single rising bubbles show a significant scattering. The reasons are discussed controversially. For instance, Tomiyama et al. [3] assume different conditions at the bubble formation process as responsible for the deviation of the various experimental data. However, it is beyond the scope of this paper to provide substantial contributions to this discussion.

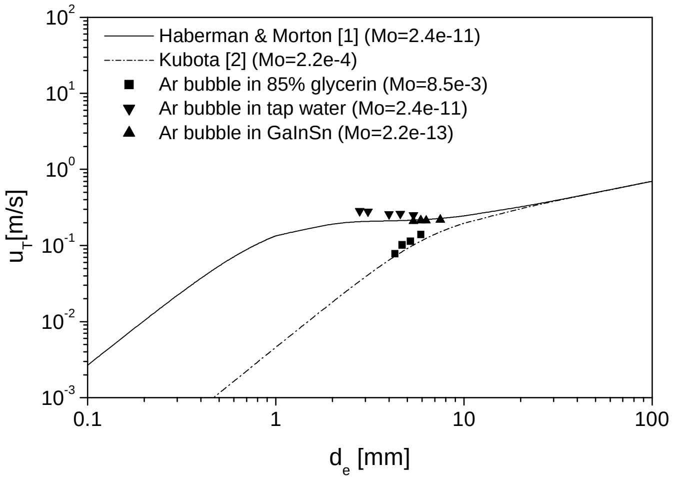


Figure 4. Bubble terminal rising velocities obtained by UDV as a function of the equivalent bubble diameter

3.3 Bubble chain driven flow

In this section we present measurements carried out in glycerin at higher gas flow rates of 0.18cm^3/s. The same experimental set-up as described in the previous section was used. At these conditions the bubbles rise in form of a chain generating also a considerable motion in the liquid bulk. Measurements of the liquid velocity in the region between the bubbles were performed by means of a LDA system (DANTEC). These data were compared with results delivered simultaneously by UDV. Because of the relatively large size of the bubbles it can be assumed that only the velocity of the liquid phase was measured by LDA.

A typical velocity profile recorded by UDV in a bubbly chain driven flow is shown in Figure 5. This profile contains two distinct bubble signals, but also some smaller narrow peaks have to be registered which cannot be related to a bubble. The occurrence of such artifacts can be explained by the multiple reflection of the ultrasonic beam at several gas/liquid interfaces before the echo arrives at the transducer. In this manner the Doppler device receives particularly velocity signals being above the liquid level at seemingly arbitrary positions. The probability to generate such artifacts increases significantly with increasing gas flow rate.

The occurrence of these artifacts has to be taken into consideration by the algorithm of data processing. Here, we have tested a special threshold method to distinguish reliably between both phase velocities. Figure 6 shows a histogram of the velocity time series measured at a distinct spatial position. It clearly shows a two-peak distribution corresponding to gas and liquid velocity, respectively. The number of recorded velocity incidents between the two peaks arises from the artifacts described above. On principle, such a distinct distribution enables us to apply a threshold method for phase discrimination.

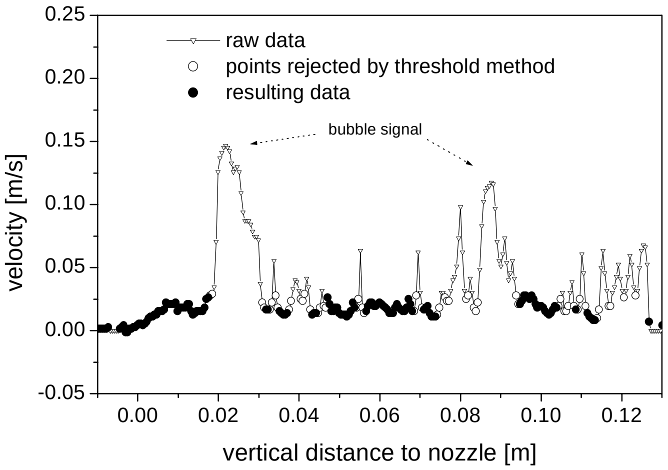


Figure 5. Raw velocity profile acquired by UDV in bubble chain driven flow and processed profile where the bubble signals and the velocity peaks created by the artifacts are removed

In a first step the bubble velocities can easily be separated from the measured profiles using a global threshold value. A more sophisticated, iterative procedure was applied to handle the velocity peaks caused by the artifacts in order to be able to extract the realistic values for the liquid velocity. After removing the bubble velocities the velocity histogram shows only one distinct peak related to the liquid velocity. Now, we evaluated all histograms obtained for the different spatial positions along the ultrasonic beam at one time step and draw another histogram based on the found peak velocities. From this histogram a threshold was determined for the liquid velocity. Because the existence of turbulent velocity fluctuations has also to be taken into account this threshold value was multiplied by a constant coefficient arbitrary set as 1.1. The velocity profiles were processed in this manner that all points above this threshold and their two spatial neighbors were rejected from the profile. The remaining gaps were rejected during the subsequent time-averaging process. This process is illustrated in Figure 5 where the curve with the open dots represents the raw velocity profile measured by UDV. The reduced profile without bubble signal and rejected points related to the artifacts is shown by the solid dots. The same algorithm was then applied for each time step during the measuring time and afterwards time-averaged profiles of the liquid velocity along the ultrasonic beam were calculated. The entire procedure was repeated several times until the threshold values obtained for each iteration were almost identical.

The development of the resulting profiles of the liquid velocity can be followed in Figure 7. At first, a threshold value of 0.03m/s was applied to eliminate the bubble velocities. The first iteration cycle provided a new threshold of 0.016m/s which was multiplied with the turbulence constant of 1.1. From the next cycle we obtained a threshold value of 0.014m/s. Further iterations were found to give the same threshold value of 0.014m/s, hence, we considered the velocity profile after the third iteration as the final result. The corresponding profile of the liquid velocity from the LDA measurements is also included in Figure 7. An excellent agreement can be noticed with the UDV profile resulting from the iterative threshold method.

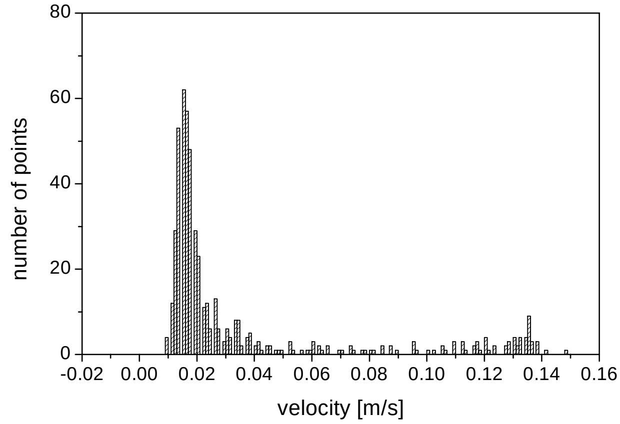


Figure 6. Histogram of the measured vertical velocity at one spatial point on the measuring line

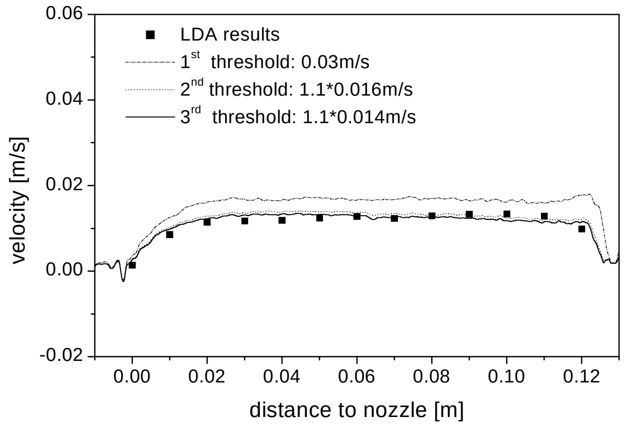


Figure 7. Time-averaged profiles of the liquid velocity resulting from different steps of the iterative threshold method Comparison of the UDV measurements with corresponding results obtained by means of LDA

Modifications of the turbulence coefficient and the number of the neighboring points to be rejected from the velocity profiles were also investigated. The turbulence coefficient was varied between 1.1 and 1.3, the number of neighboring points were changed between 2 and 14. However, as can be seen in Figure 8 the influence of variations of both parameters on the final results can be considered to be very small.

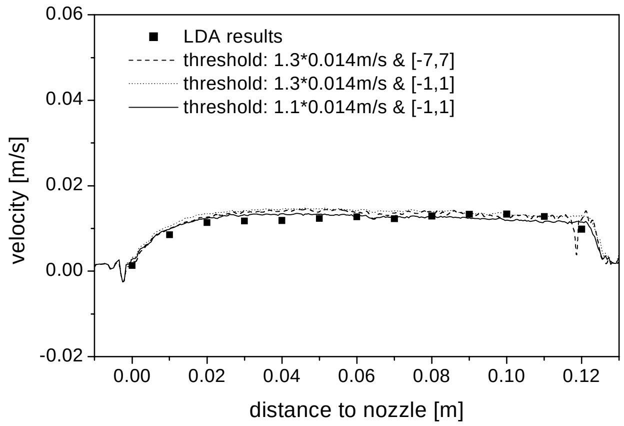


Figure 8. Effect of modifications of the turbulence coefficient
and the number neighboring points to be eliminated on the final results

The above discussions are only related to the present experimental conditions. Alterations of flow conditions can result in a considerable change of the quality of the Doppler signal. If the void fraction will be significantly increased or the bubble sizes will be much larger, a widespread appearance of artifacts caused by multiple echoes must be expected. It is not clear if the iterative threshold method in the presented form will also provide reliable results for higher gas flow rates. But, also different methods might be available. Thus, additional information such as the echo amplitude could be used to improve the analysis. For instance, questionable peaks could be rejected from the velocity profiles if bubble signatures cannot be identified simultaneously at corresponding positions in the echo amplitude. These problems are in the focus of further investigation.

3.4 Single bubbles rising in a liquid metal affected by a D.C. magnetic field

The influence of a D.C. magnetic field on the motion of a single bubble rising in a liquid metal was investigated. Eutectic GaInSn having a melting point of about 10°C was chosen as liquid allowing us to work at room temperature using a cylindrical container made from Perspex. The ultrasonic transducer was acoustically coupled outside at the bottom wall of the cylinder just below the orifice. Two water-cooled copper coils in a distance of 150mm were positioned axially centered around the fluid container (see Figure 9). Such a Helmholtz configuration provides a homogeneous magnetic field in the domain between both coils. The direction of the magnetic field lines is directed parallel to the axis of the fluid cylinder. The coils were supplied with a D.C. current up to 1000A resulting in a maximum magnetic field strength of about 0.19T.

A single orifice with an inner diameter of 0.3mm or 1.0mm was used. The gas flow rate was adjusted in the range from 0.002-0.02cm^3/s leading to intervals between two consecutive bubbles larger than 10s. From these data the mean equivalent bubble diameter was determined to be between 5.4-7.5 mm corresponding to an Eotvos numbers of 3.4-6.6. The results we present here have to be considered as preliminary.

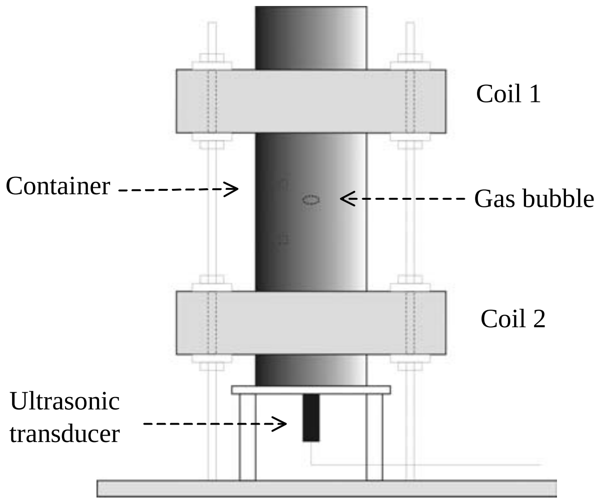


Figure 9. Set-up of the GaInSn experiment

The terminal velocity u_T was measured for different magnetic field strengths B and the drag coefficient C_D was calculated using equation (1). The results for the drag coefficient as function of the magnetic interaction parameter N are drawn in Figure 10. The magnetic interaction parameter $N = \sigma_{el} B^2 L / (\rho u_T)$ is a measure of the ratio between the electromagnetic and the inertial forces. Here, σ_{el} and ρ stand for the electrical conductivity and density, respectively, of the fluid

($\sigma_{el} = 3.27 \times 10^6 \Omega^{-1} m^{-1}$ for GaInSn). The bubble diameter d_e was taken as typical length scale L. Figure 10 shows a slight decrease of the drag coefficient with increasing N. This tendency can be observed for all considered Eotvos numbers.

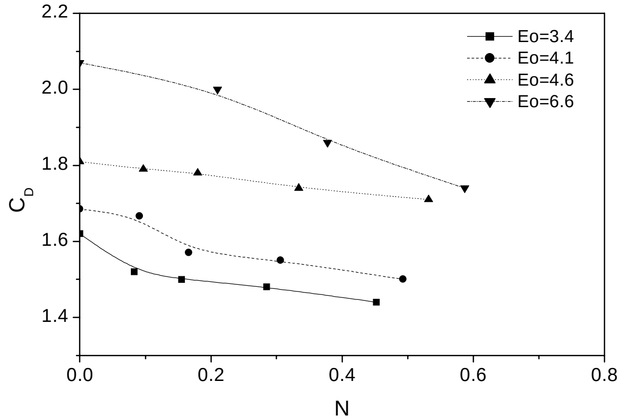


Figure 10. Bubble drag coefficient as function of the magnetic interaction parameter N deduced from UDV measurements in GaInSn in longitudinal magnetic fields

Velocity profiles behind a bubble are displayed in Figure 11 for cases without magnetic field and a field strength of 0.19T. These snapshots were acquired at time steps if the bubble was detected at the same spatial position. The profiles show the velocity peak related to the rising bubble and the subsequent wake. It becomes obvious that the structure of the wake has been modified due to the magnetic field effect. In the case without magnetic field the vortex structure of the wake can be clearly found in the signal. If the process is exposed to a longitudinal magnetic field the wake becomes more uniform. The velocity gradient along the field lines is reduced. The velocity peaks in the near bubble region are significantly damped. On the other hand, the velocity in the far region was found to be higher indicating longer decay times of the wake in case of magnetic field application. Our investigations on this topic will be continued.

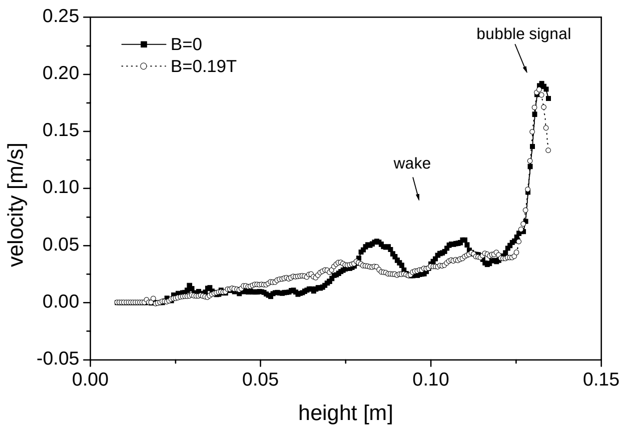


Figure 11. Vertical velocity profiles showing the bubble wakes with and without application of a D.C. longitudinal magnetic field (Eo=4.64)

4. Conclusions

The Ultrasonic Doppler Velocimetry (UDV) was applied to measure simultaneously both liquid and bubble velocities in bubbly flows at low gas flow rates. Water, glycerin and the eutectic alloy GaInSn were used as liquids characterized by large variations with respect to their material properties. This allowed us to perform our investigations in quite different parameter regions.

The structure of the velocity signals obtained by UDV has been analyzed. In the region of the low gas flow rates considered in this paper it was possible to clearly distinguish between the bubble and the liquid velocities. In the single bubble region the vertical component of the bubble velocity can be determined accurately. The UDV signal also allows a detailed analysis of the corresponding wake structure. Isolated artifacts occur in the velocity signal if the gas flow rate is increased until attaining a bubble chain driven flow. For such flow structure an iterative threshold method was presented to obtain correct profiles of the liquid velocity. A comparison regarding time averaged velocity profiles of the liquid phase delivered by UDV and measurements performed with LDA show an excellent agreement.

A measuring program has been started to study the influence of an external magnetic field on the motion of bubbles rising in liquid metals. First results received from a GaInSn column exposed to a longitudinal magnetic field show a slight decrease of the drag coefficient with increasing magnetic field strength at magnetic interaction parameters smaller than one. The measurements reveal a distinct effect of the magnetic field on the bubble wake.

Acknowledgement

The research is supported by the Deutsche Forschungsgemeinschaft (DFG) in form of the SFB 609 "Electromagnetic Flow Control in Metallurgy, Crystal Growth and Electrochemistry". This support is gratefully acknowledged by the authors.

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