Determination of the flow structure in bubble-driven liquid metal flows using ultrasound Doppler method

Chaojie Zhang, Sven Eckert and Gunter Gerbeth
MHD Department, Forschungszentrum Rossendorf , 01314 Dresden, Germany

The ultrasound Doppler velocimetry (UDV) was validated for its capability to measure both gas and liquid velocities in transparent as well as opaque two-phase flows. A special threshold method has been tested successfully for processing of UDV data acquired from bubble-driven flows. Our experimental work presented here is focused on the influence of a transverse static magnetic field on a bubble plume in a cylindrical vessel. The liquid flow field has been measured by means of the ultrasound Doppler velocimetry. Despite the well-known damping effect of a DC magnetic field, it was observed, that the application of a moderate magnetic field may also cause an intensification of the liquid recirculation. The global flow field was found to be dominated by quasi-two-dimensional large scale vortex structures, whose axes are parallel aligned with the magnetic field direction. Therefore, the time-averaged flow field shows a distinct anisotropy. Local recirculating zones are found in the meridional plane perpendicular to the magnetic field lines, while velocity distributions become more uniform in the other plane parallel to the magnetic field.

Keywords: bubble plume, liquid metal, magnetic field, ultrasound Doppler velocimetry.

1 INTRODUCTION

Magnetic fields are widely used to control the melt flow in metallurgical engineering, which directly governs the heat and mass transfer rate and hence the final product quality [1, 2]. 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 contact-less way. Well-controlled laboratory experiments equipped with suitable measuring techniques can deliver us a deeper insight into the physical process encountered in real industrial application.

Owing to the induced electromagnetic force, static magnetic fields are known to be suitable for damping mean and turbulent flow in metallic melts. However, several investigations concerning thermal convection in liquid metals revealed to some extent an enhancement of convective heat transfer at moderate DC magnetic fields [3-5]. Measured temperature signals displayed periodical oscillations with large amplitudes indicating that the global flow field becomes time-dependent. Large scale vortex structures were assumed to occur, which are very efficient for the transport of heat. In this paper we present some experimental results obtained from a study of a bubble plume in a cylindrical vessel exposed to a transverse DC magnetic field

Recently, the ultrasound Doppler velocimetry became an attractive non-intrusive measuring technique especially for determining velocity profiles in opaque fluids such as liquid metals [6, 7]. Previous studies have demonstrated its capability in MHD flow measurements, and especially, in two-phase flows [8 - 11].

2 EXPERIMENTAL SET-UP

Figure 1 shows a sketch of the experimental configuration. The eutectic alloy GaInSn was stored in an open cylindrical vessel made of Plexiglas with an inner diameter of 90 mm. The height of the liquid metal bulk is 220 mm leading to an aspect ratio of $A = H/D = 2.44$. Argon bubbles were injected through a single nozzle at the center of the container bottom and rise up in a region around the cylinder axis. A mass flow controller (MKS 1359C) was utilised to adjust the gas flow rate in a range between 0.3 and 7 cm^3/s. Such low gas flow rates were selected to ensure the formation of a dispersed bubbly flow regime.

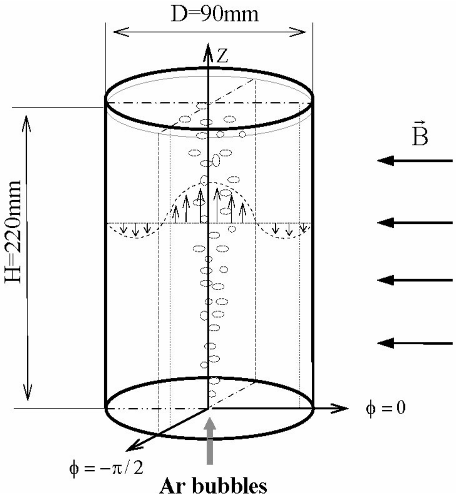


Figure 1: Sketch of the experimental set-up showing the bubble plume driven flow exposed to a transverse static magnetic field

A pair of water-cooled copper coils provides a static transverse magnetic field covering homogeneously the full volume of the liquid metal. The field strength scales with the non-dimensional Hartmann number, indicating the ratio between the electromagnetic force and the viscous force,

$$\mathrm{Ha} = BR\sqrt{\frac{\sigma}{\rho\nu}}$$

where σ, ρ and ν denote the electrical conductivity, the density and the kinematic viscosity of the fluid. *B* is the magnetic field strength and *R* the radius of the fluid vessel.

The DOP2000 velocimetry (Model 2032, Signal-Processing, Lausanne, Switzerland) equipped with a standard 4 MHz (TR0405LS) has been used to perform the velocity measurements. Both the vertical and radial component of the liquid phase velocities were measured by coupling the transducer at the outer container wall. The transducer position was controlled by a traversing mechanism. The measurements at different spatial positions allowed for a flow mapping in the sense of time averaged velocity field. The scan rate of the consecutive velocity profiles was adjusted to 27.5 Hz by setting a 2370 Hz pulse repetition frequency and 60 bursts per profile. At each position, 6000 velocity profiles were recorded corresponding to a time period of 218 s, which was found to be sufficient for giving reliable time-averaged results. The measuring volume can be considered as a series of discs lined up concentrically along the ultrasound beam, due to the divergence of the beam, the lateral size of the measuring volumes is increasing with the distance from the transducer. In the present measurements, we achieved a spatial resolution of 0.69 mm in axial direction and 10.5 mm in lateral direction at the distance of 100 mm ahead of the transducer. The ultrasound Doppler method has shown its capability to measure simultaneously both liquid and bubble velocities in bubbly flows at low gas flow rates [9]. It is possible to clearly distinguish between the bubble and the liquid velocities in the region of low gas flow rates. In the case of single bubbles the method enables a detailed analysis of the bubble wake structure [10]. 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 developed 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 showed an excellent agreement. A detailed description can be found in [9].

3 RESULTS AND DISCUSSION

Since the impact of the DC magnetic field is anisotropic with respect to the field direction we focus on the flow field in two orthogonal mid-planes being parallel and perpendicular to the magnetic field lines, respectively. The time-averaged flow pattern obtained at a gas flow rate of 0.33 cm^3/s are shown in figure 2 (a) and (b) for the ordinary and the MHD case at Ha = 271, respectively. The velocity distributions of an ordinary bubble plume are quite analogous in both orthogonal planes. The liquid is driven upward in the central region due to the rising bubbles, whereas a global recirculation with poloidal structures is generated close to the container wall. The flow field becomes anisotropic if the bubble plume is exposed to the magnetic field. Strong vertical structures with axes parallel to the magnetic field lines appear in the plane perpendicular to B.

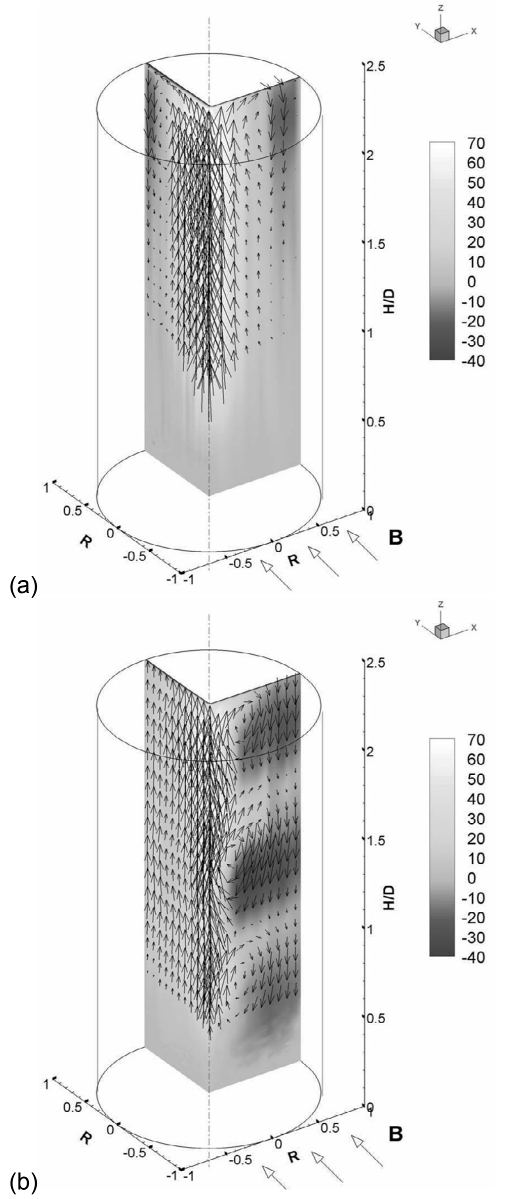
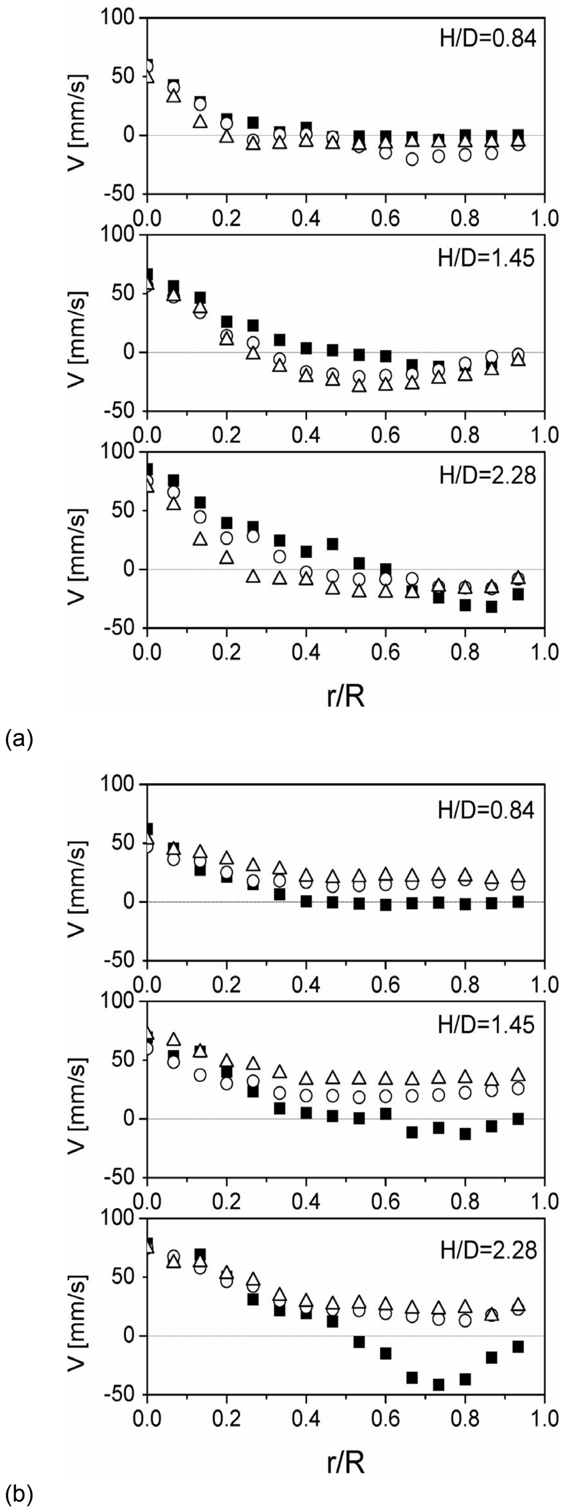


Figure 2: Contour and vector plots showing the vertical velocity and the 2D flow field (r-z-plane), respectively.
(a) *B* = 0; (b) *B* = 0.16 T. Positive values correspond to upward flow, and negative values to downward flow. The velocities are in unit of mm/s. (Q_g = 0.33 mm^3/s)

Generally, the recirculation in the perpendicular plane is amplified and extended over the entire height of the cylinder. In the plane parallel to the magnetic field a suppression of descending and promotion of ascending flow can be observed.



(a)

(b)

Figure 3: Radial distributions of the liquid velocity at different heights and Hartmann numbers, (a) in the plane perpendicular to B; (b) in the plane parallel to *B*. For both figures (a) and (b) the symbols denote
_ *Ha* = 0; _ *Ha* = 271; _ *Ha* = 484. (Q_g = 0.83 $\mathrm{mm^3/s}$)

Equivalent velocity measurements at higher gas flow rates revealed qualitatively analogue flow pattern. Figure 3 displays radial distributions of the vertical velocity obtained at several vertical positions. The liquid flow in the ordinary bubble plume can be considered as almost axisymmetric. The rising bubbles generate an ascending flow around the container axis, while the maximum of recirculation occurs at larger radial positions close to the wall closely beneath the free surface. Especially in the lower region of the vessel, an intensification of the descending flow in the perpendicular plane appears with applied magnetic field. In the plane parallel to B the liquid is solely flowing upwards resulting in a plug-like uniform velocity distribution.

The modification of the flow structures described above is consistent with the theoretical predictions as discussed by Davidson [12] for the case of an axisymmetric jet flow under the influence of a transverse magnetic field. The evolution of the flow structures is governed by the minimization of the Joule dissipation. This is the explanation for the observation, that the cross-sectional area of the jet has been stretched along the field lines direction. The velocity distribution tends to become independent of the coordinate parallel to the magnetic field direction, since the existence of considerable velocity gradients in the field line direction is the reason for the induced current. Finally, the velocity field becomes quasi-two-dimensional.

The redistribution of momentum by the electromagnetic force as described above is responsible for a distinct modification of the transient flow behaviour, too. To illustrate this, the spatial-temporal distribution of the vertical velocity component is displayed in figure 4.

In figure 4, the z-coordinate is normalized with the total height of the container *H* to represent the spatial position, which is plotted along the ordinate. The abscissa of the figure corresponds to the time scale. Each figure is composed of a consecutive series of velocity profiles acquired in a period of two minutes. Compared to the ordinary flow shown in figure 4 (a), the relatively weak magnetic field gives rise to a state of oscillating flow in a large part of the container. The oscillating structure shows a periodicity of about 25 s. In the plane perpendicular to the magnetic field, wave-like flow structures are formed at the free surface. A spot with a strong, i.e. downwards directed, velocity is quasi-periodically moving from the free surface downwards. Reaching approximately the middle of the container it returns abruptly to the surface region. In the lower part of the cylinder between *z/H* = 0 and 0.2, there appears a layer of enhanced descending flow compared to that of the ordinary case without magnetic field. Qualitatively similar, but inversed flow structures can be found in the plane parallel to *B*. Further measurements at various gas flow rates and magnetic field intensities inclusive detailed description and discussion can be found in [11].

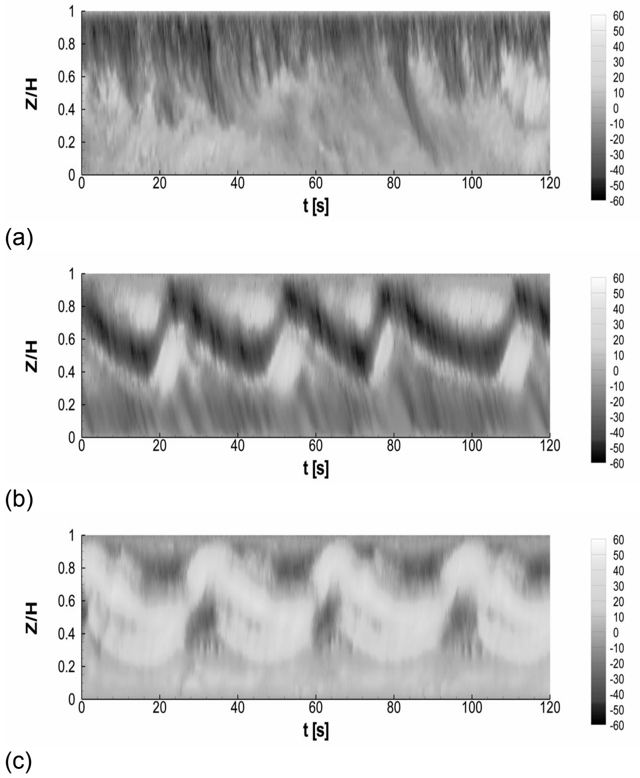


Figure 4: Spatial-temporal distributions of the vertical component of liquid velocity measured at the radial position of r/R = 0.87, (a) Ha = 0; (b) Ha = 271, in the plane perpendicular to B; (C) Ha = 271, in the plane parallel to B. For all the figures, the dark colour represents downward flows, bright colour represents upward flows. The velocity values are given in mm/s.

4 SUMMARY

The paper presents an experimental study of the bubble-driven liquid metal flow exposed to a transverse magnetic field. The characterization of the flow field inside the melt was carried out using the ultrasound Doppler technique.

The experimental results reveal the main impact of the magnetic field in a modification of the flow pattern to become anisotropic with respect to the magnetic field direction. The cross section of the bubble-driven jet being circular in the case of an ordinary bubble plume is elongated along the magnetic field direction. This leads to an intensification of descending fluid flow in the plane perpendicular to B and correspondingly an intensification of ascending flow in the plane parallel to B. The plug-like velocity profile found in the planes parallel to the field lines are similar compared to the phenomenon of the Hartmann profile occurring in MHD channel flows.

The fluid motion was found to be dominated by large scale structures elongated along the magnetic field direction over the entire chord lengths of the circular cross section. For moderate Hartmann numbers the vertical position of these vertical structures oscillates. Particularly, even counter-rotating vortices appear. The occurrence of such vertical structures is supposed to explain the intensification of the convective heat transfer as observed in MHD thermal convection [3-5]. At higher Hartmann numbers the motion of the vertical structures will be suppressed, obviously associated with a reduction of the transfer properties.

The two-fold influence of a static magnetic field needs to be taken into account for electromagnetic flow control by DC magnetic fields in industrial processes, for instance the use of an electromagnetic brake for the continuous casting of steel.

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