Ultrasonic flow measurements and bubble detection in gas-stirred metallic melts

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In this study we investigate the flow structure in a liquid metal cylinder while a bubble-driven recirculation flow is superposed with a rotating magnetic field (RMF). The flow structure and the bubble positions were measured by means of the ultrasound Doppler velocimetry (UDV) and the ultrasound transit-time technique (UTTT), respectively. The measurements revealed the potential of the RMF to control both the amplitude of the meridional flow and the bubble distribution and to provide an effective mixing in the entire fluid volume. Various periodic flow patterns were observed in a certain parameter range with respect to variations of the magnetic field strength and the gas flow rate.

Keywords: Bubble detection, Bubble flow, rotating magnetic field, mixing

1 INTRODUCTION

Bubble-driven flows are widely used in industrial technologies. In metallurgical applications gas bubbles are injected into a bulk liquid metal in order to force a motion, to homogenize the physical and chemical properties of the melt or to refine the melt [1,2]. Another way to drive a liquid metal into motion is the application of a rotating magnetic field (RMF) [3,4].

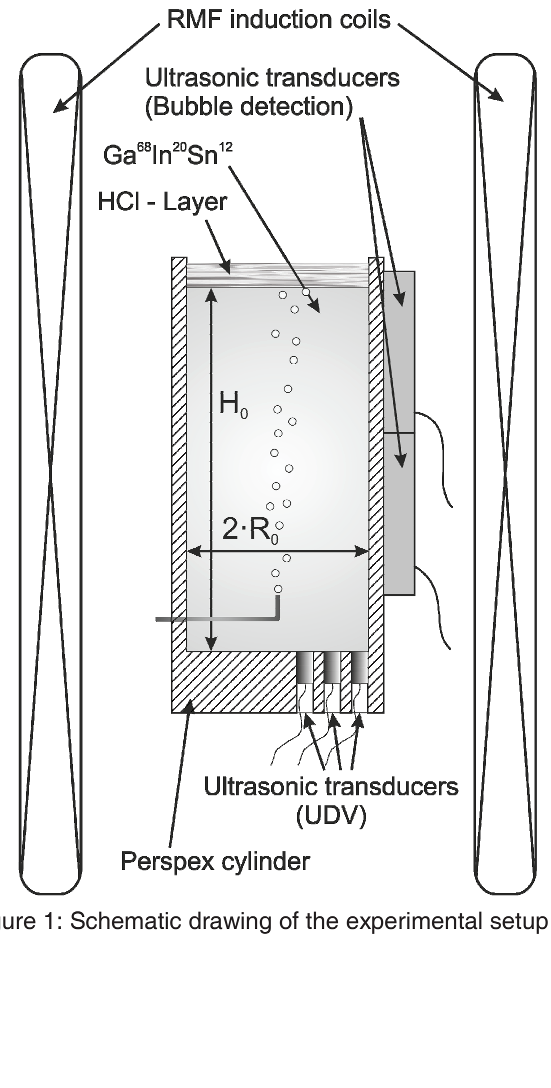

Figure 1: Schematic drawing of the experimental setup

In this study we investigate the flow structure in a liquid metal cylinder while these two different driving mechanisms are used simultaneously. A schematic drawing of the experimental setup is shown in Fig. 1. A cylindrical vessel having an inner diameter of 90 mm and an aspect ratio $A = H_0/(2*R_0) = 2$ was filled with the eutectic alloy GaInSn, which is liquid at room temperature. The cylinder was placed concentrically in the magnetic induction system PERM at the Helmholtz-Zentrum Dresden-Rossendorf (HZDR). The PERM stirrer was equipped with six coils, arranged as pole pairs in order to create a rotating magnetic field with a field strength up to 17 mT. The magnetic field frequency was fixed to $\omega = 2\pi 50$ Hz. Argon gas was injected with an adjustable flow rate in the middle of the cylinder bottom. The fluid velocities were measured using the ultrasound Doppler velocimetry (UDV). For that purpose we placed five ultrasound transducers at the bottom of the fluid container. The transducers were aligned vertically in order to record axial profiles of the vertical velocity between the bottom and the lid of the fluid cylinder at different radial and azimuthal positions. The detection of the gas bubbles in the liquid metal was realized by means of a ultrasound transit-time technique [5]. Two ultrasonic heads, each consisting of 10 ultrasonic transducers, were placed horizontally at different heights at the sidewall of the cylinder. An ultrasound defectoscope (USIP 40) together with the software UltraPROOF (both from GE Inspection Technologies) were used to calculate the bubble position from the transit time of the ultrasound signal from the transducer to the bubble and return. The time resolution of the measuring system is about 2.5 ns. Twenty ultrasound transducers were allocated along the vessel side wall to monitor the full vessel height while only 10 transducers could be multiplexed. For a particular measurement the respective 10 transducers were selected according to the best compromise with respect to a suitable detection of the bubble path variations.

2 RESULTS

Depending on the gas flow rate Q_G (sccm stands for standard cubic centimeters per minute) and the magnetic field strength (expressed by the magnetic Taylor-number) we observed five main flow regimes. The Taylor number is defined as follows

$$Ta = \frac{\sigma \omega B_0^2 R_0^4}{2\rho \upsilon^2} \qquad (1)$$

where σ stands for the electrical conductivity, ρ is the density and υ is the kinematic viscosity of the fluid.

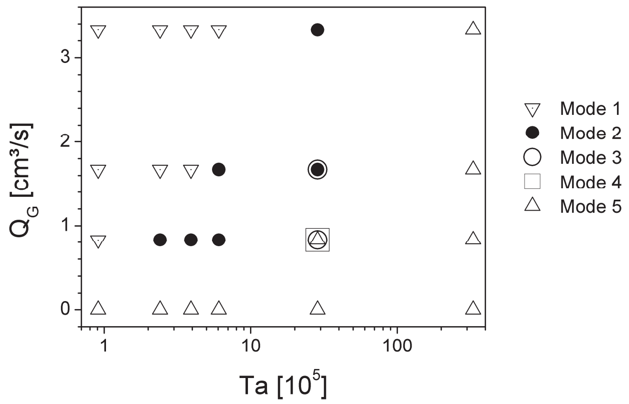

Figure 2: Map of the specific flow patterns at different parameter combinations

When the rising bubble plume is superposed with a low power RMF, the flow pattern in the cylinder consists of a recirculation zone in the upper half of the cylinder which is almost identical to the bubble plume without a magnetic field (in the following denoted with “mode 1”). In the opposite, if the bubble-driven flow is exposed to a very strong RMF, the resulting strong swirling motion forces the bubbles to the rotational axis of the vessel (mode 2). The resulting flow pattern consists of the well-known double vortex of the RMF-driven flow in the meridional plane of the vessel [6-7]. In between these two limiting parameter regimes we observed three new flow patterns (mode 3 – mode 5) showing a remarkably oscillating behavior of the velocity field. The parameter range where the different flow modes were observed is shown in Fig 2.

Mode 3 is a flow pattern characterized by very high fluid velocities in the entire flow volume. Fig. 3 shows an UDV measurement of this flow pattern. Here, the bubble plume is rising off-axis at approximately r ≈ 0.3 * R_0 and produces a large recirculation zone that occupies almost the entire fluid volume. Furthermore, this flow configuration rotates around the vessel axis in the same direction as the RMF. Fig. 4 shows the corresponding histogram of the spatial distribution of the bubbles for ten transducers positioned at increasing distance

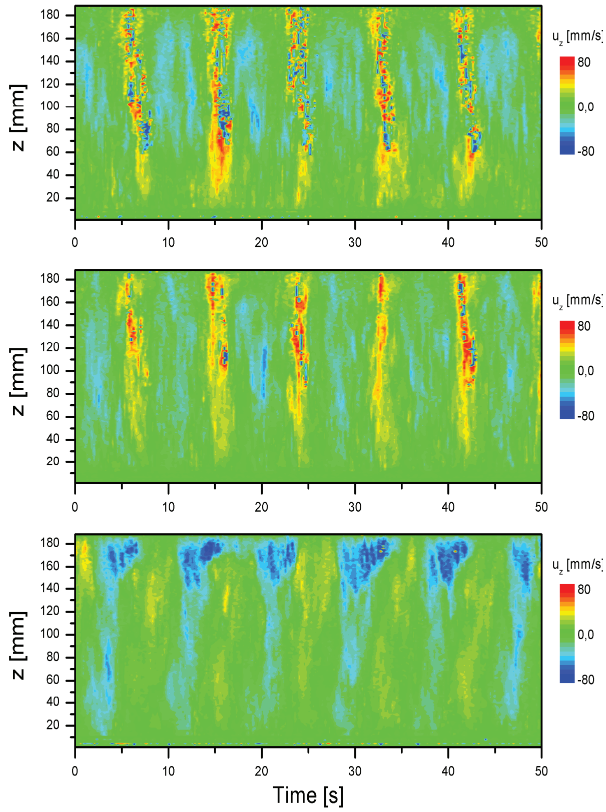

Figure 3: Periodic flow pattern (mode 3) resulting from the superposition of RMF (B = 1 mT) and rising gas bubbles (Q_G = 100 sccm); UDV measurements are recorded at r/R_0=0.3 (top), r/R_0=0.6 (middle) and r/R_0=0.9 (below)

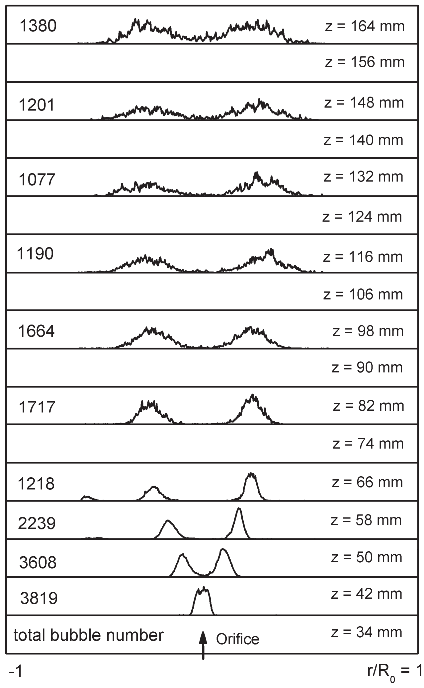

Figure 4: Bubble histogram corresponding to the measurements shown in Fig. 2. Q_G = 100 sccm; B = 1 mT (Ta = 28,6 * 10^5); ΔT = 360 s

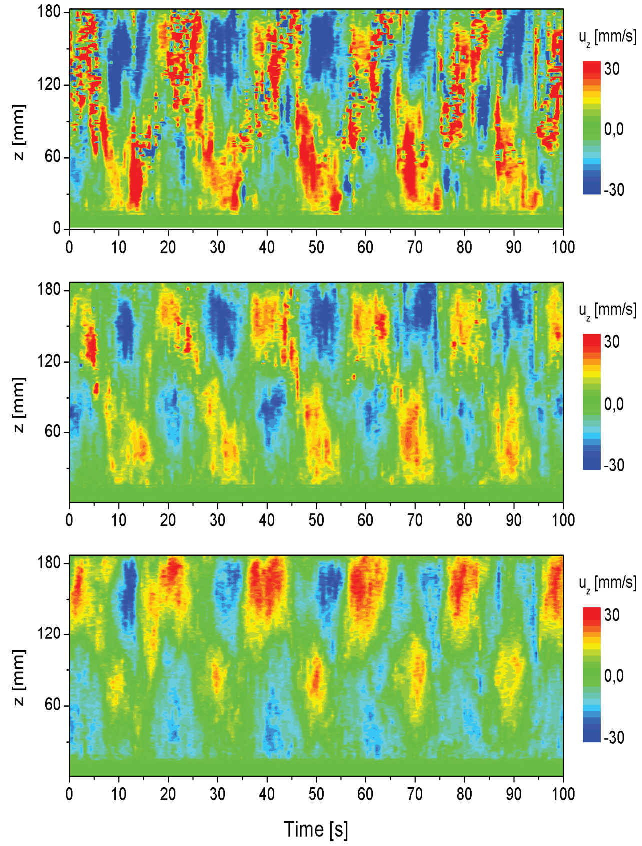

Figure 5: Periodic flow pattern (mode 4) resulting from the superposition of RMF (B = 1 mT) and rising gas bubbles (Q_G = 100 sccm); UDV measurements are recorded at r/R_0=0.3 (top), r/R_0=0.6 (middle) and r/R_0=0.9 (below)

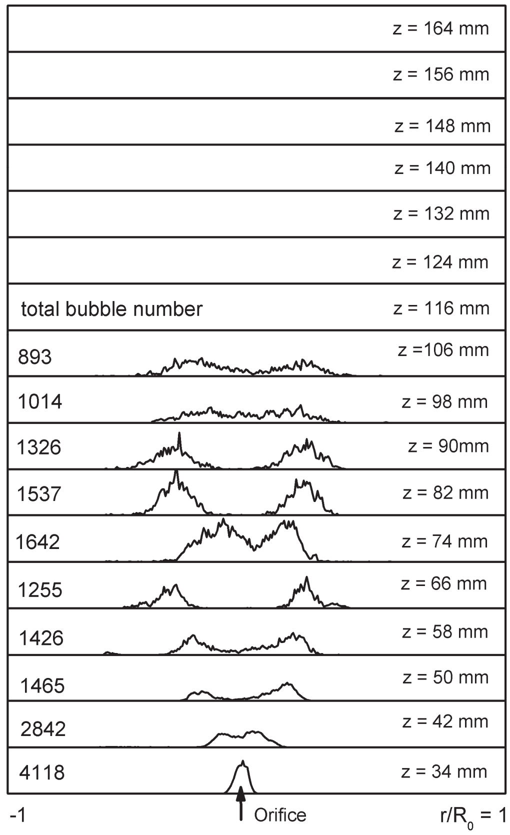

Figure 6: Bubble histogram corresponding to the measurement shown in Fig. 5. Q_G = 100 sccm; B = 1 mT (Ta = 28,6 * 10^5); ΔT = 360 s

from the orifice. The value on the left hand side in the histogram is the total number of bubbles detected by each transducer within the measuring interval of ΔT = 360 s. This value decreases in z-direction due to the increase of the radial spreading of the gas bubble distribution during their rise. The key information of these bubble histograms is the spatially varying bubble distribution over the cross section of the vessel.

A further remarkable flow pattern that was observed in our experiments is shown in Fig. 5 - 6. This flow mode, which is denoted with mode 4, differs from mode 3 by the S-shaped bubble path. This S-shaped bubble path produces two recirculation zones. A schematic drawing of both, mode 3 and 4 is shown in Fig 7.

The last flow pattern - mode 5 - is very similar to the pure RMF induced swirling flow (mode 2). The only difference is a weak oscillation of the fluid flow in the center region of the vessel due to the rising gas bubbles.

3 CONCLUSION

In our experiments we studied the flow in a liquid metal cylinder which is driven by the superposition of a rising bubble plume and a rotating magnetic field. Both driving mechanisms are used separately

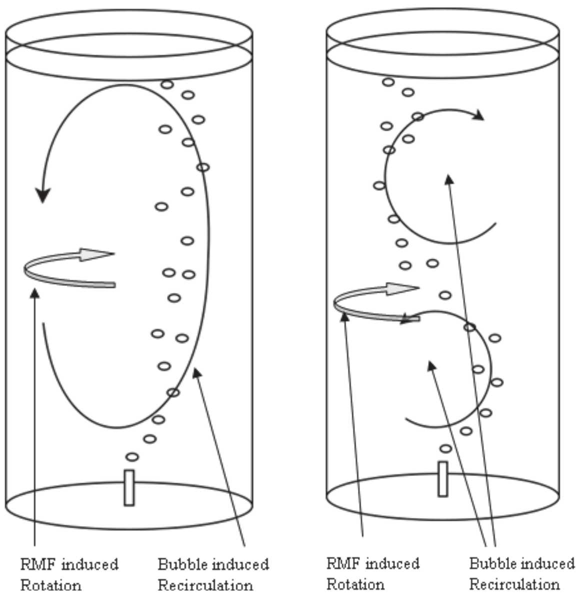

Figure 7: Schematic drawing of the periodic flow patterns mode 3 and mode 4

in metallurgical applications for purposes of melt stirring. Likewise, the resulting flow structure was studied in depth in many experiments and numerical simulations. In contrast, the flow structure resulting from the simultaneous usage of rising bubble plume and RMF is a rather low explored flow configuration.

We found out that the superposition of these two driving mechanisms within a distinct parameter range yield some striking new flow patterns of oscillating nature. These flow patterns are attributed with increasing fluid velocities in the whole fluid volume. In addition, the undesired dead water zones, which occur in pure bubble driven recirculation flows, can effectively be avoided. Therefore, this new flow configuration has a high potential to increase the efficiency of metallurgical applications where a high mixing rate is desired.

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