# FLOW PATTERN FORMATION IN A LIQUID METAL COLUMN BY PULSED EXCITATION OF A ROTATING MAGNETIC FIELD

Dirk Räbiger[*], Tobias Vogt[*], Sven Franke[*,**], Jürgen Czarske[**], Sven Eckert[*a)] & Gunter Gerbeth [*]
[*]*Helmholtz-Zentrum Dresden-Rossendorf, 01314 Dresden, Germany*
[**]*Technische Universität Dresden, 01069 Dresden, Germany*

*Summary* We present an experimental study concerning measurements of the flow inside a liquid metal column exposed to a pulsed rotating magnetic field. A novel ultrasound Doppler system was used to measure two-dimensional velocity fields of the secondary flow in the radial-meridional plane. It employs an array of 25 transducer elements allowing a fast electronic traversing with concurrently high spatial and temporal resolution. The measurements revealed transient flow regimes showing distinct inertial oscillations and coherent vortex structures.

## INTRODUCTION

Electromagnetic stirring during solidification has been proved to be a striking method for achieving a purposeful alteration of the microstructure of casting ingots, such as grain refinement or the promotion of a transition from a columnar to an equiaxed dendritic growth (CET). However, the imposition of a rotating (RMF) or a travelling magnetic field (TMF) also causes problems like the occurrence of typical segregation pattern or a deflection of the upper free surface. It was shown recently, that the application of modulated AC magnetic fields offers remarkable potential to overcome the handicaps of rotary stirring with the specific goal to generate a vigorous stirring in the bulk without considerable deformations of the free surface [1, 2]. Especially, the secondary flow can be organized in such a way that periodic reversals of the flow direction occur adjacent to the solidification front, which has been proven as an important method to prevent flow-induced macrosegregation [3]. It became apparent that a careful adjustment of the modulation parameters is required in order to create intense secondary flows with periodic reversals of the flow direction. Within this paper we especially consider the effect of a pulsed RMF on the isothermal liquid metal flow inside a circular cylinder, whereas the RMF is applied in form of successive rectangular pulses. Previous investigations revealed the existence of an optimal pulse length $T_P$, where a maximum intensity of a periodic meridional flow can be observed [2]. In that case the corresponding pulse frequency $f_P$ relates to the eigenperiod of inertial waves in a developed regime, as given by Greenspan [4]. The present study is aimed at highly resolved, quantitative velocity measurements in order to disclose the flow pattern resulting from various modulated driving forces differing with respect to the respective pulse length.

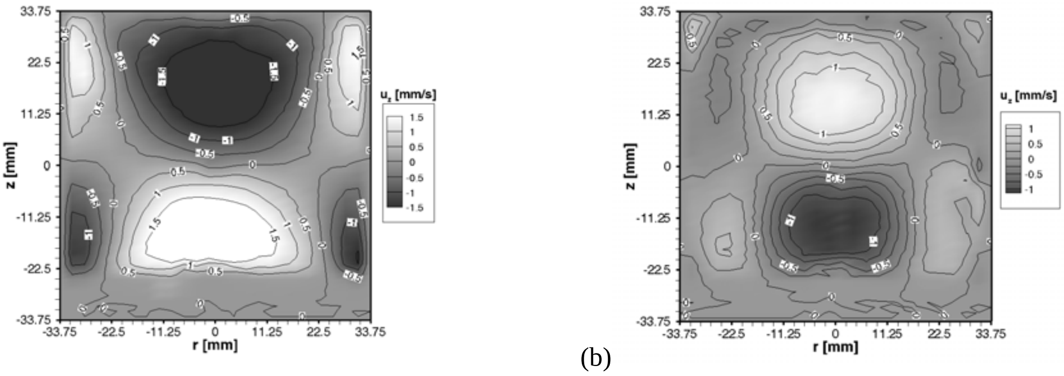
## EXPERIMENTAL SETUP

A detailed description of the experiment can be found in [2]. A cylindrical vessel made of Plexiglas was used with an aspect ratio $A = H_0/2{\cdot}R_0 = 1$. The size of the inner diameter of $D = 2{\cdot}R_0$ and the height $H_0$ was chosen to be 67.5 mm. The cylinder is closed by rigid lids and filled with the eutectic alloy GaInSn. The experiments were performed in the magnetic induction system PERM at HZDR, wherein the fluid vessel was placed concentrically. The ultrasound Doppler velocimetry (UDV) was used to perform measurements of the fluid flow. The DOP2000 velocimeter (model 2125, Signal Processing SA, Lausanne) equipped with a 4 MHz transducer was applied to measure the primary azimuthal flow at two vertical positions. By attaching the ultrasonic transducer to the wall of the fluid container, the acoustic coupling between sensor and fluid was realized through the curved cylindrical surface. Moreover, a flow mapping of the meridional flow was realised by using a new measuring system operating with a linear array of 25 single transducers attached to the plane-parallel bottom wall of the flow container. Details of the measuring system are given in [5].

## RESULTS

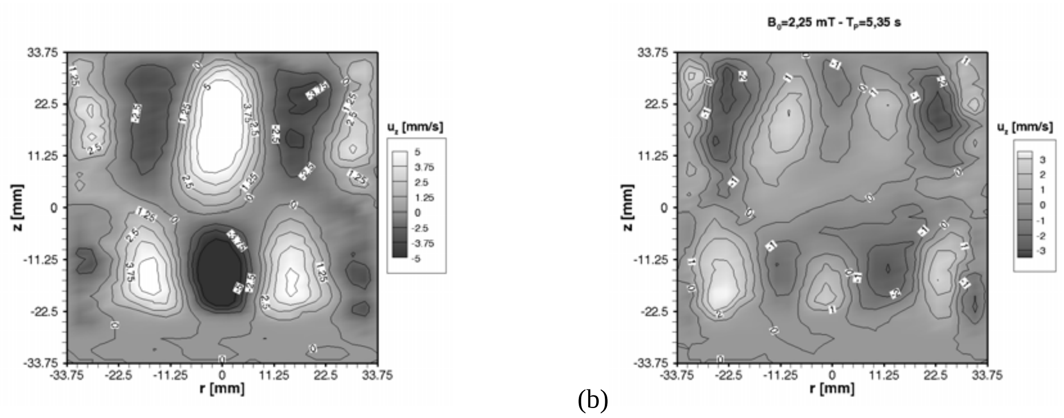
As a consequence of the application of a pulsed RMF the fluid flow experiences a sequence of spin-up and spin-down processes. The duration of the particular pulse cycles $T_P$ turns out to be a crucial control parameter. Measurements of both the primary and the secondary flow have been carried out for different values of $T_P$. Figure 1 displays contour plots of the vertical flow pattern obtained for a pulse cycle of $T_P$ = 20 s at B = 0.46 mT. The typical secondary flow structure in form of the toroidal double vortex can be detected in figure 1(a). The flow in the central region is directed upwards in the bottom part and downwards in the upper part of the cylinder, respectively. An inversion of the flow direction, a so-called “inverse” double vortex, occurs in figure 1(b). Figure 2 shows two snapshots of the vertical flow obtained at $B$ = 2.25 mT for pulse durations of $T_P$ = 4.3 s and 5.3 s, respectively. It is interesting to note that new flow pattern emerge marked by an increment of vortex cells in radial direction.

a) Corresponding author. Email: s.eckert@hzdr.de




(a) (b)

Figure 1: Snapshots of the vertical velocity across the vertical mid-plane of the cylinder ($T_P$ = 20 s, $B$ = 0.46 mT): (a) typical double vortex of the secondary flow; (b) "inverse" double vortex




(a) (b)

Figure 2: Snapshots of the vertical velocity as in figure 1 for $B$ = 2.25 mT: (a) $T_P$ = 4.3 s; (b) $T_P$ = 5.3 s

## DISCUSSION AND CONCLUSIONS

The present study concerns a liquid metal flow being exposed to a pulsed RMF. The alternating power up and power down of the magnetic field generates successive spin-ups and spin-downs of the rotating fluid flow. Abrupt changes in energy injection rates promote the propagation of inertial waves through the interior of the fluid [6, 7]. Because the Coriolis force balances the pressure gradients and generates the restoring force for the inertial waves, their wavelengths and frequencies are related in a special way. The theoretically determined eigenperiod $\tau$ of the inertial waves was given by Greenspan [4]:

$$\tau = \frac{\pi}{\Omega}\left[1 + (\gamma_i / n\pi)^2 (H_0 / R_0)^2\right]^{1/2} \qquad (1)$$

where $\gamma_i$ denotes the i$^{th}$ root of the Bessel function $J_1(x)$ (for reference, $\gamma_1$ = 3.832, $\gamma_2$ = 7.016, $\gamma_3$ = 10.174). The angular rotation rate $\Omega$ was determined from our measurements. Considering the axisymmetric inertial mode $k$ = 0, $n$ = 2, $m$ = 1 we obtain eigenperiods of 20.6 s and 3.1 s for magnetic field intensities of 0.46 mT and 2.25 mT, respectively. These results agree very well with the experimentally identified $T_P$ values related to the main resonance peaks. A prolongation of the pulse duration $T_P$ at 2.25 mT produces further inertial modes. These higher modes manifest themselves in new secondary flow pattern showing an incremented number of vortex cells in radial and axial direction. The parameter region around the main resonance frequencies appears as optimal working region for an efficient electromagnetic stirring. The permanent reversals of the flow direction make this flow regime promising for applications in directional solidification processes. The electromagnetic stirring method that uses a modulated RMF offers considerable potential to enhance the stirring efficiency and to optimize the properties of castings by a well-aimed flow control during solidification.

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