# VISUALIZATION OF THE FLOW STRUCTURE AND TEMPERATURE FIELD IN THE REGION OF MIXED CONVECTION

Elzbieta Fornalik[*], Wolfgang Leiner [**], Janusz S. Szmyd [*], Tomasz A. Kowalewski [***] and Hiroyuki Ozoe [****]

[*]*AGH University of Science and Technology, PL 30-059 Krakow, Poland*

[**]*Ruhr University of Bochum, D 44780 Bochum, Germany*

[***]*Polish Academy of Sciences, IPPT PAN, Swietokrzyska 21, PL 00-049 Warszawa, Poland*

[*****]*Kyushu University, 6-1 Kasuga Koen, Kasuga, 816 – 8580 Fukuoka, Japan*

*Summary* The results of experimental simulation of mixed convection in the process of single-crystal growth by Czochralski method are presented. Visualizations were done by dispersed encapsulated liquid crystals, which enable simultaneous measurements of the velocity and temperature fields. Experimental analysis was done for the cylindrical vessel kept in the isothermal conditions. Velocity fields showed appearance of vertical structures, whose number, shape and movement depend strongly on the Reynolds number. Velocity vectors maps are compared with the isotherms.

## INTRODUCTION

Developments of microelectronic industry for modern applications require rigorous size and quality control of crystalline materials. The Czochralski method together with the Bridgman method is one of the crystal growth techniques for large-scale production, especially for oxide and semiconductor materials [1]. The convection in the melts during single crystal growth of semiconductors and oxides significantly affects the quality of the crystal grown from the melts in Czochralski crystal growth systems [2]. Therefore it is very important to understand melt motion and fluctuation of temperature in the melt for higher quality and larger size of single crystals.
The process of crystal growth by Czochralski method is widely discussed in the scientific literature. There are many areas of interests in both fields the numerical simulation and the experimental analysis of that process. The numerical simulation is more often discussed, for example Basu et al. [3], Akamatsu et al. [4], Enger et al. [5], who described the process under different conditions. The publications based on the experiments were rarely found in the past, but it can be said that lately their number increased [5], [6], [7], [8]. The authors of presented paper concentrated on the detailed structure of the flow field and the corresponding temperature field in the region of mixed convection, which can lead to better understanding of the phenomenon and to predict the optimal conditions.

## EXPERIMENTAL APPARATUS AND PROCEDURE

Experimental apparatus is presented in figure 1. The mixed convection phenomenon was studied in the cylindrical glass vessel (crucible) **(6)** of inner diameter $D$ = 0.094 m, placed into the glass cubic container **(5)**. The space between the crucible and the outer wall was filled by a thermostatic fluid maintaining the system in constant temperature. The cylindrical vessel **(6)** was filled by the mixture of glycerol and water, which was studied as an experimental fluid. To the free surface of mixture the copper cylinder **(4)** of diameter $d$ = 0.022 m was attached. It was supplied from above by a vertical rotating shaft, which was driven by a DC-motor **(1)** provided by an adjustable power supply. A Peltier element **(3)** was fitted between the shaft and the copper cylinder simulating the crystal (4) served to maintain a temperature difference between these both and consequently equally between the inner pool simulating the melt and the copper cylinder simulating the crystal. The upper part of apparatus was covered by a cooling jacket **(2)**.

### Essential Parameters

The physical similarity of the experiment was kept as close to the original process of crystal growth as possible, therefore in the present studies the fundamental parameters are the non-dimensional numbers: the Prandtl number (Pr = 14.8), the Grashof number (Gr = 115 555) and the Reynolds number (Re = 0, 5, 10) (eqs. 1)

$$\mathrm{Pr} = \frac{\nu}{a}, \qquad \mathrm{Gr} = \frac{g\beta\Delta T R^3}{\nu^2}, \qquad \mathrm{Re} = \frac{R_x^2\Omega_x}{\nu} \tag{1}$$

where $\nu$ - kinematic viscosity, $a$ – thermal diffusivity, $g$ – gravitational acceleration, $\beta$ - thermal expansion, $\Delta T$ – temperature difference, $R$ – "crucible" inner radius, $R_x$ – "crystal" radius, $\Omega_x$ – angular velocity.

### Experimental methods

In the experiment the liquid crystals were applied for the velocity and temperature measurements. The velocity field was measured by DPIV method. The liquid crystals slurries were added into the mixture of glycerol and water in the crucible. They cover the temperature range of colour indication from 26.1 $^{o}$C to 43.3 $^{o}$C. To obtain the colour temperature field, the particular cross-section was illuminated by the white light sheet generated by the halogen lamp.

The digital image processing was applied to transform the colour images into the velocity vectors maps and data representing temperature fields.

## RESULTS

The typical structure of the flow in a region of natural convection (Re = 0, temperature difference is set-up to be 5 K) is presented in figure 2. Two vortical counter-rotating structures can be observed. Just below the "crystal-simulating cylinder" the experimental fluid was cooled and it moved toward a crucible bottom. Then the stream of cooled fluid spread toward the side walls. In the vicinity of the side walls the fluid was warmed up and its ascending movement could be observed. In figure 3 velocity vectors map for Re = 10 is presented. The flow field showed very characteristic shape – two very large vortical structures in the central part of crucible, two vortices near side walls due to natural convection and just below the "crystal" two very small vortices. The fluid near the walls moved upward while the descending movement of cooled fluid was observed not below the "crystal" but on its sides. Just below the crystal fluid changed direction and moved upward. Whole structure is very complicated and it is difficult to present it in 2D. The temperature field is not presented here because of the place shortage.

## CONCLUSIONS

In this paper the experimental simulation of mixed convection in the case of single crystal growth by Czochralski method was presented. The visualisation of the temperature and velocity field was done by dispersed encapsulated liquid crystals. The temperature images were compared to the velocity fields obtained by DPIV method. Interaction between the natural and forced convection generated very complicated structures, which are not symmetrical. In the central part of crucible, direction of fluid flow was changed, which can have an influence on the mass transfer. The temperature field became more homogeneous than in the case of natural convection.

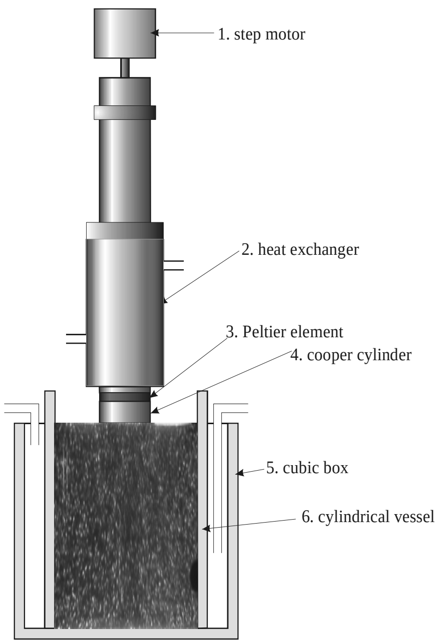


Figure 1. Schematic view of experimental equipment.

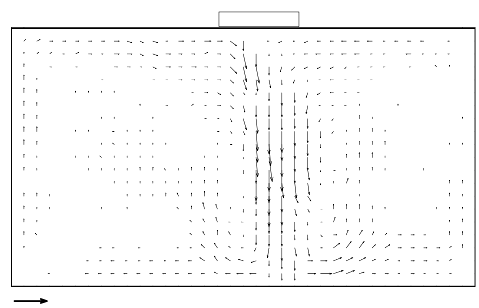

Figure 2. Velocity vectors map, Re = 0.

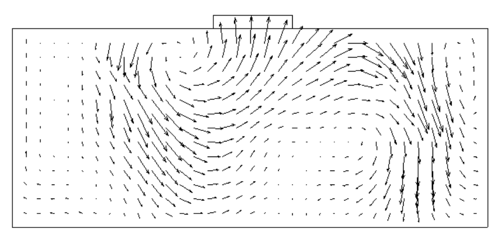

Figure 3. Velocity vectors map, Re = 10.

## References


[1] Yoon J. K., Yi K. W.: Modelling of Transport Phenomena in Crystal Growth. WIT Press, Southampton 2000.

[2] Kakimoto K.: Modelling of Transport Phenomena in Crystal Growth. WIT Press, Southampton 2000.

[3] Basu B., Enger S., Breuer M., Durst F.: Effect of rotation on the three-dimensional mixed convection in the oxide melt for Czochralski growth. *J. Crystal Growth*, **230**: 148-154, 2001.

[4] Akamatsu M., Higano M., Ozoe H.: Elliptic temperature contours under a transverse magnetic field computed for a Czochralski melt. *Int. J. Heat and Mass Transfer*, **44**: 3253-3264, 2001.

[5] Enger S., Basu B., Breuer M., Durst F.: Numerical study of three-dimensional mixed convection due to buoyancy and centrifugal force in an oxide melt for Czochralski growth. *J. Crystal Growth*, **219**: 144-164, 2000.

[6] Aleksic J., Szymczyk J.A., Leder A., Kowalewski T.A.: Experimental investigations on thermal, thermocapillary and forced convection in Czochralski crystal growth configuration. Computational Methods and Experimental Measures. WIT Press, 2001.

[7] Hintz P., Schwabe D.: Convection in a Czochralski crucible – Part 2: rotating crystal. *J. Crystal Growth*, **222**: 356-364, 2001.

[8] Ozoe H., Toh K., Inoue T.: Transition mechanism of flow modes in Czochralski convection. *J. Crystal Growth*, **110**: 472-480, 1991.