MULTI-CHANNEL METHOD FOR MEASURING THE VELOCITY FLOW PATTERN IN CLOSED VOLUMES

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Introduction. The developed [1, 2] multi-channel system for measuring the temperature field at modelling CZ semiconductor single crystal growth has demonstrated a number of interesting results for the instability of the "cold" melt at the interface and for a "drop" (or jet) convection in CZ single crystal growth, for the stabilizing role of the crucible rotation, as well as has reveled some peculiarities of the influence by steady and alternating magnetic fields on the melt hydrodynamics, etc. At the same time, the direct investigations of the pattern and strength of hydrodynamic flows could obviously supply more information about the CZ-process than the investigations of the temperature field.

1. Method and procedure of multi-channel measurements. Each conductive velocity probe was produced from a cylinder-shaped small samarium-cobalt magnet (diameter – 2 mm, height – 2 mm). Electrodes, made of isolated copper wire 0.1 mm in diameter, were placed at the edges of the small magnets. The probes were arranged on a special grid composed of 5 horizontal rods of 2 mm in diameter, made of stainless (non-magnetic) steel and joint by 2 vertical rods. The probes protrude by about 12 mm outward the grid plane. Since the set is meant for velocity flow measuring in the meridional plane of the crucible, the above protruding has to significantly decrease the impact of the grid on measurement results. By a special joint unit (connector) the assembly of probes is connected to the block of amplifiers.

To strengthen signals from the conductive probes, nanovolt amplifiers were used (EM Electronics Company, The Rise Brockenhurst, Hampshire, SO42 7SJ, England). The amplifiers have been preliminary calibrated and their serviceability has been tested within the range of signals $U = 0 - 1$ μV. Preliminary tests have demonstrated a linear dependence of input to output voltage values. The level of pulsations (noise) was also comparatively low. Therefore, the amplifier can be used to measure signals from conductive anemometers, while measuring the flow velocity patterns.

Before the experiments, the measuring probes were calibrated in a specially produced setup. Calibrating allowed to define and save the sensibility of all 32 probes as well as the coefficients for calculating the legitimate signal from nanovolts to cm/s. The set of probes was newly calibrated prior to each series of experiments. Upon calibration, the set of probes was placed inside the crucible, filled with InGaSn melt, and arranged in the meridional plane. The main goal of the experiments was to adjust the measuring method, procedure and software used for studying the flow velocity pattern in CZ single crystal growth. Fig. 1 schematically illustrates the experiments conducted under the isothermal regime.

Comparatively large sizes of the crucible (diameter – 500 mm, melt level – 150 mm) allowed, as a first approximation, to ignore the impact from the set of probes on the flow velocity pattern. Reference points were measured and data recorded by a special program for each probe separately. Then electromagnetic stirring was switched on. After being held under the conditions of electromagnetic

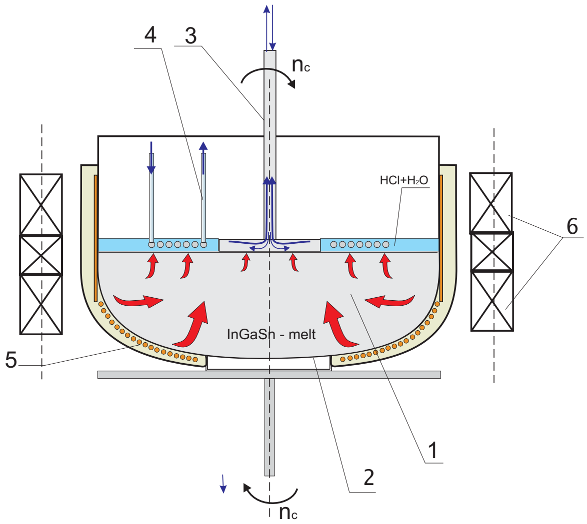


Fig. 1. Schematic of the experimental facility. 1 – melt, 2 – crucible, 3 – crystal model, 4 – heat exchanger, 5 – heater, 6 – magnetic system of AC and travelling magnetic field.

stirring for about 15 minutes, measurements began. The measuring procedure was the same as for the temperature field [1, 2]. During about 16 minutes with a 1-sec interval 1000 instant distributions of the radial melt flow velocity component were registered. Those instant distributions of the radial velocity component allowed instant pictures of the distribution of stream function ψ and root-mean square scatter ψ^*:

$$\psi = \frac{1}{N}\sum_{i=1}^{N}\psi_i \qquad \psi^* = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(\psi_i - \psi)^2}\,,$$

where ψ_i denote instant values of the stream function, ψ is the mean value, $N = 1000$ denotes the number of measurements.

2. Main results and discussion. Experiments were carried out in an alternating (AC) axial field and in a travelling magnetic field (TMF).

2.1. Experiments in an AC-field. The data obtained in the AC-field are illustrated in Figs. 2, 3. Let us first discuss the experimental results for the radial velocity component V_r versus the time t. During every experiment, the data on instant values of the radial velocity component were registered at 32 points in the meridional plane of the crucible and PC-processed. As an example, Fig. 2 shows some data for V_r obtained at $NI = 5000$ A at two points in the melt. A typical feature of these results is a high amplitude and frequency of velocity pulsations.

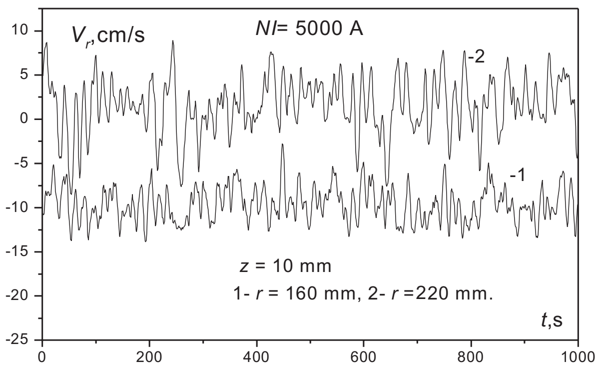


Fig. 2. Pulsations of the V_r velocity component at $NI = 5000$ A.

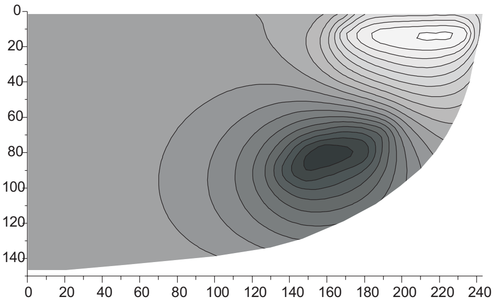


Fig. 3. Stream function ψ in the AC-field at $NI = 5000$ A.

Table 1.

NI, A	$\psi_{\max}$, m^3/s	$\psi_{\min}$, m^3/s	ψ^*, m^3/s
2000	2.20E-04	-1.60E-04	2.50E-05
3000	2.71E-04	-2.73E-04	2.95E-05
4000	3.00E -04	-4.14E-04	3.12E-05
5000	3.61E-04	-3.51E-04	3.17E-05

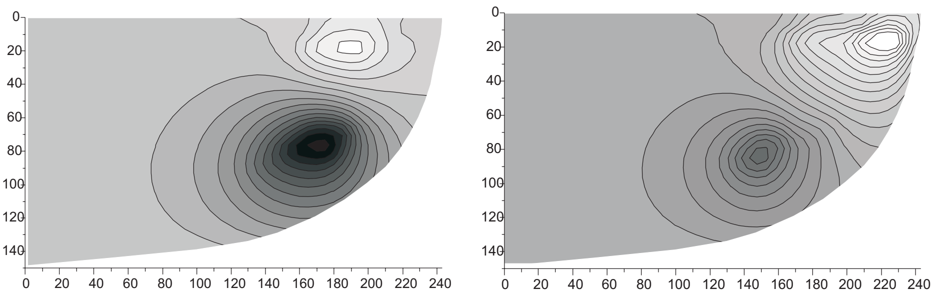
One can clearly see that the amplitude of velocity pulsations (curve 2) can be much higher than the mean velocity.

When such data recalculated for all channels, the mean and instant distributions of the stream function ψ and root-mean scatter ψ^* have been obtained.

Some mean distributions of the stream function ψ obtained under the AC-field at NI = 5000 A are illustrated in Fig. 3. In this picture and further on dark colour denotes eddies, rotating clockwise, lighter colour – eddies, rotating anti-clockwise.

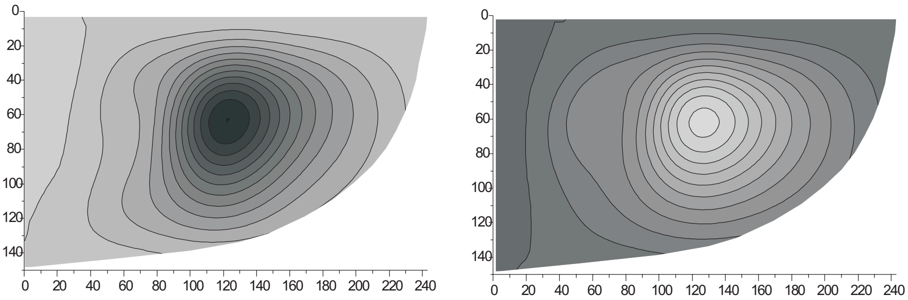
Isolines ψ, in general, disclose a two-vortex melt flow pattern – a vortex at the free surface is very pronounced. Mean data for the flow pattern almost do not depend on the parameter NI. As NI increases, only maximum and minimum values of ψ increase – Table 1.

Instant distributions ψ are illustrated in corresponding video animations. Video animations include 100 instant pictures, varying every second, and testify to a fast enough and substantial modification of the melt flow pattern with the time. Moreover, the vortical patterns maintain their intensity and move within the melt volume. Fig. 4 clearly illustrates the instant distributions ψ at two different moments of time. Fig. 4*a* displays maximum values of ψ for a vortex at the crucible bottom and minimum values for a vortex at the melt free surface. Opposite situation is illustrated in Fig. 4*b*.



(*a*) (*b*)

Fig. 4. Instant distributions of stream functions ψ for the AC-field.



(*a*) (*b*)

Fig. 5. Stream functions for the travelling magnetic field at $NI_{\mathrm{TR}} = 5000$ A.

Table 2.

NI_{TR}, A	$\psi_{\max}$, m^3/s		$\psi_{\min}$, m^3/s	ψ^*, m^3/s
3000	"down"	1.75E-04	-1.95E-04	1.23E-05
4000	"down"	1.80E-04	-4.60E-04	1.80E-05
5000	"down"	2.65E -04	-7.20E-04	2.00E-05
6000	"down"	3.80E-04	-8.26E-04	2.47E-05
3000	"up"	4.72E-04	-6.70E-05	1.05E-05
4000	"up"	4.60E-04	-2.23E-04	1.37E-05
5000	"up"	6.60E -04	-3.11E-04	1.50E-05
6000	"up"	8.36E-04	-3.72E-04	1.66E-05

2.2. Experiments in a TMF. Similar data for a travelling magnetic field (TMF) at the angle of shift between the coils of 60° and at the linear current being 5000 A are disclosed in Fig. 5.

In the middle of the crucible, one can see vortical structures, rotating clockwise when the travelling magnetic field runs "downwards", and they rotate anticlockwise when the travelling magnetic field runs "upwards". The flow is single-vortex; maximum and minimum values of the stream functions increase, as the NI_{TR} – parameter increases – Table 2.

So, the obtained experimental results testify to a possibility to use the developed systems for multi-channel measurements of velocity for investigations of the melt flow velocity patterns when simulate the CZ crystal growth as well.

REFERENCES

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