NUMERICAL MODELING OF 2D AXISYMMETRIC FLOW UNDER THE INFLUENCE OF AC OR DC EM FIELDS FOR INDUSTRIAL CZ SINGLE CRYSTAL SILICON GROWTH FACILITIES

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Introduction. The Czochralski (CZ) method is the most important industrial single-crystal silicon-growth method, and it accounts for about 95% of the total annual silicon crystal growth output. Nowadays, the modern silicon single-crystal CZ growth industry develops electromagnetic field systems to influence the silicon melt movement in growth facilities, and numerical modeling plays an important role in reducing the development costs. One of the key elements in the modeling of the CZ crystal growth is numerical modeling of the turbulent silicon melt flow and heat transfer. The applicability of widely used turbulence models, based on k-ε approach, for modeling industrial CZ growth is not certain; therefore, these models need experimental verification.

The numerical modeling of the melt flow in the crucibles of the industrial CZ growth systems and laboratory models under various 2D axisymmetric AC and DC EM fields, as well as under 3D DC magnetic fields, is described in, for example, [1, 2]. The current article presents selected results of numerical modeling of the axisymmetric melt flow as well as comparison between the calculations and temperature measurements in a laboratory model of the CZ growth facility with an InGaSn low-temperature melt in a 20″ crucible. The modeling of the turbulent melt flow and heat transfer has been carried out by the authors for the 2D axisymetric Chien low-Re-number k-ε turbulence model. A new modification of this model is also proposed. A more detailed analysis of the flow under the 2D AC EM fields is presented in [2].

1. Summary of the numerical results obtained by the Chien low-Re-number k-ε turbulence model. Here, selected numerical modeling results and experimental data are presented for the melt flow in the crucible without any EM field influence and for the melt flow under the influence of a "down" TMF and a CUSP magnetic fields. Fig. 1 shows the outline of the laboratory model and the meridional stream function distributions for the three above-mentioned cases. Fig. 2 shows meridional distributions of the numerically simulated and measured temperature and temperature fluctuation distributions for the case without any EM field. Fig. 3 and 4 show the temperature and temperature fluctuation distributions for the cases with the "down" TMF (60° phase shift and 1667 Aw inductor current strength) and with the CUSP magnetic field (70 mT near the crucible bottom), respectively.

The comparison between the calculated and measured temperature distributions shows that the numerical modeling results qualitatively agree with the

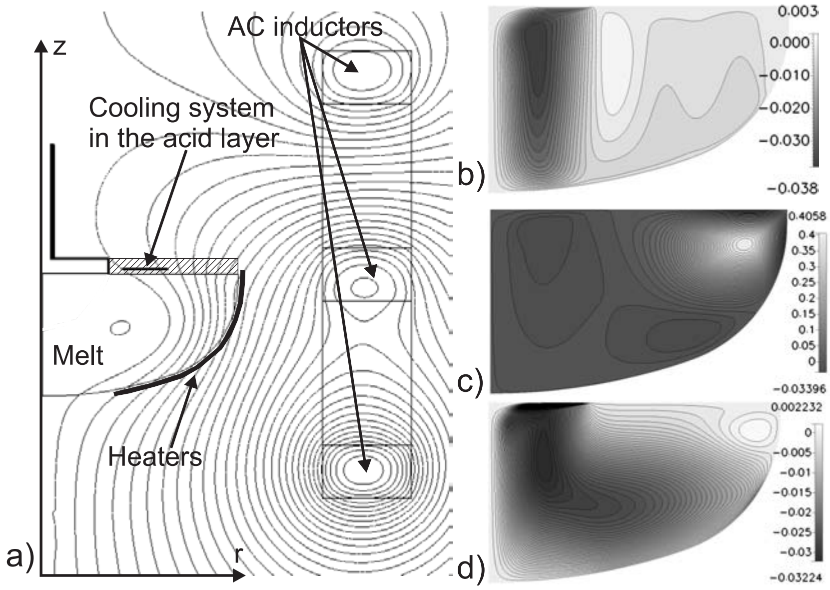

Fig. 1. (a) The outline of the laboratory model with the EM inductor system with the distribution of the azimuthal component of the magnetic vector potential A_ϕ (real part). Stream function distributions in m^3/s for the melt flow under no EM field influence (b), under the influence of a "down" TMF ((c), 60° phase shift between the inductor currents, 1667 Aw), and under the influence of 70 mT CUSP magnetic fields (d). $\Omega_{\text{crystal}} = 15$ rpm, $\Omega_{\text{crucible}} = -5$ rpm.

measurement data. The numerical modeling shows similar patterns in meridional temperature distributions in the outer zone of the crucible and a similar dependency of temperature distributions on the strength of the applied AC EM fields. The calculation results for the cases with the DC magnetic fields also agree with the measurement data, but not so well as for the cases with the AC fields. Despite of overall good agreement, there are also significant discrepancies between

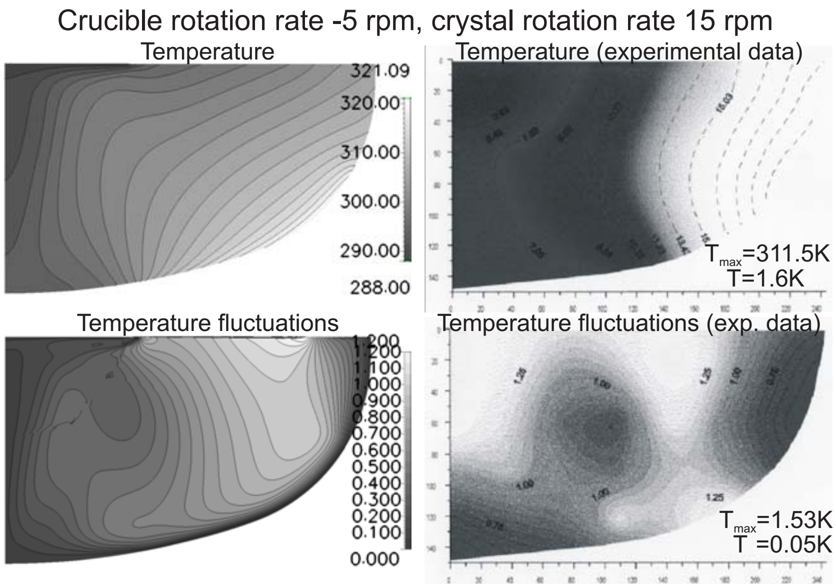

Fig. 2. The melt flow without any EM field influence. Numerically modeled (left) and measured (right) temperature and temperature fluctuation distributions (in K).

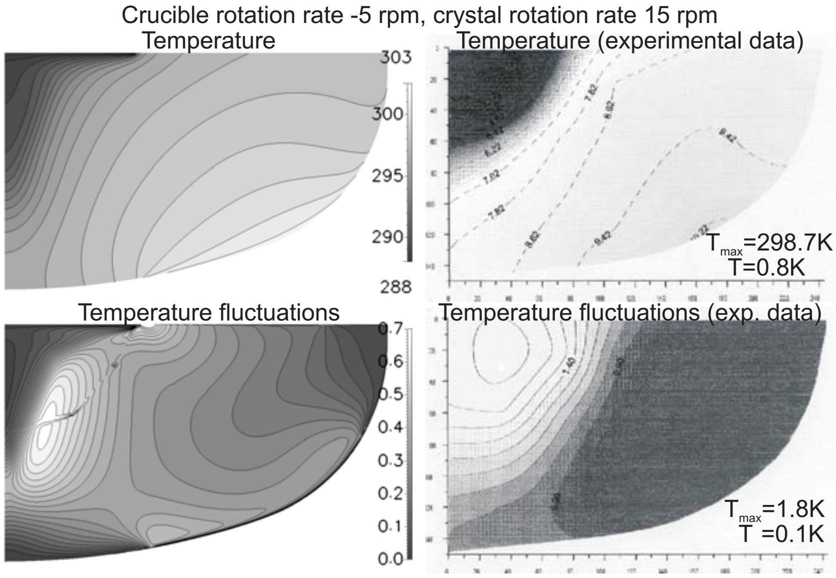

Fig. 3. The melt flow under the influence of the "down" TMF with 60° phase shift and 1667 Aw current strength. Numerically modeled (left) and measured (right) temperature and temperature fluctuation distributions.

the modeling and measurement data for the melt flow in the region under the crystal. In the calculations, there appears a long vertical and narrow zone with low temperatures directly under the crystal.

These results do not agree with the measurement data, which show that there is no long and narrow zone with low temperatures under the crystal. Also, the measured maximum temperature difference $\Delta T = T_{\max} - T_{\min}$ is significantly lower than the calculated one. These discrepancies are very important for the crystal growth modeling, since the flow distribution near the crystallization interface in-

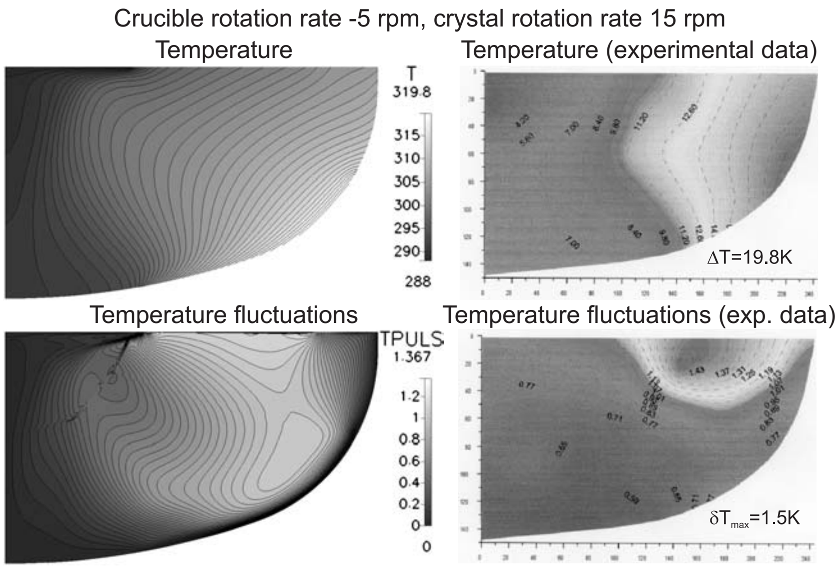

Fig. 4. The melt flow under the influence of the 70 − mT CUSP magnetic field. Numerically modeled (left) and measured (right) temperature and temperature fluctuation distributions.

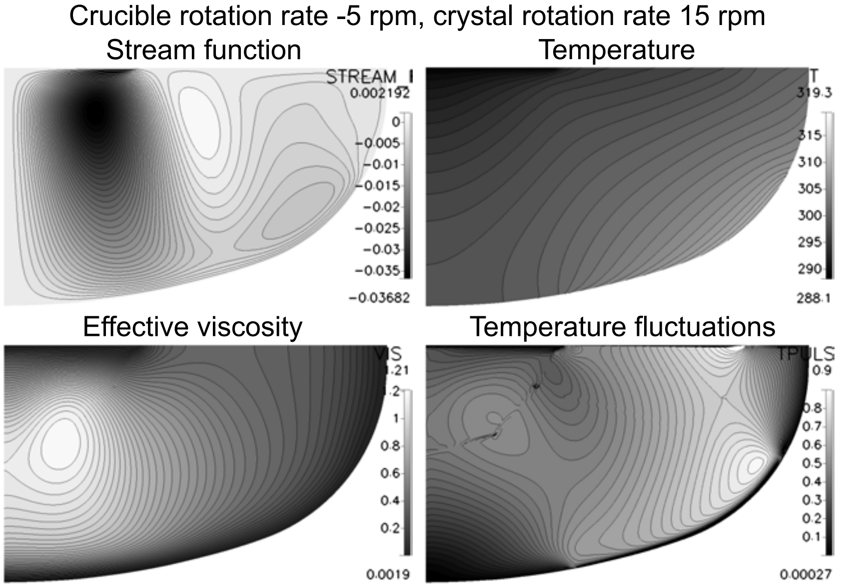

Fig. 5. The melt flow without any EM field influence. The results of numerical modeling with the modified low-Re-number k-ε turbulence model. The meridional distributions of stream function (m^3/s), temperature (K), effective viscosity ($Pa \cdot s$), and temperature fluctuations (K).

fluences the properties and quality of the grown crystals.

2. A new modification of the Chien turbulence model. To solve this problem, we propose a new modification of the Chien low-Re-number k-ε model with an additional source term S_{add} for the turbulent kinetic energy k:

$$S_{\text{add}} = c_{\text{coeff}} \eta_{\text{turb}} \left(\frac{\partial v_r}{\partial z} - \frac{\partial v_z}{\partial r} \right)^2 , \tag{1}$$

where η_{turb} is the turbulent dynamic viscosity, and c_{coeff} is a non-dimensional coefficient (for details see [3]). The numerical modeling results with the modified model (see Fig. 5) have shown several improvements, specifically the disappearance of the narrow zone with low temperatures under the crystal and the decrease of the maximum temperature difference ΔT, which becomes closer to the experimental value.

3. Conclusions. The Chien low-Re-number k-ε turbulence model describes satisfactorily the melt motion under the influence of axisymmetric AC and DC magnetic fields in the whole crucible, except the region beneath the crystal. The proposed new modification of the turbulence model improves the agreement with the experiment in the region under the crystal.

REFERENCES

1. A. Krauze, A. Muižnieks, A. Mühlbauer, Th. Wetzel, W. von Ammon. Numerical 3D modelling of turbulent melt flow in large CZ system with horizontal DC magnetic field–I: flow structure analysis. *J. Crystal Growth*, Vol. 262 (2004), no. 1-4, pp. 157–167.

2. A. Krauze, A. Muiznieks, A. Mühlbauer, Th.Th. Wetzel, L. Gorbunov, A. Pedchenko, J. Virbulis. Numerical 2D modelling of turbulent melt flow in CZ system with dynamic magnetic fields. *J. Crystal Growth*, Vol. 266 (2004), no. 1-3, pp. 40–47.

3. A. Krauze. Mathematical modelling of turbulent melt flow under the influence of AC and DC magnetic fields in CZ crystal growth system. Ph.D. thesis, 2005.