

the pressure can be eliminated. In this condition, vorticity is formed in fluid. So momentum equations can be written in curl form

$$\nabla^2 (\nabla \times \vec{u}) = \nabla^2 \omega = 0 \quad (6)$$

where $\omega = \nabla \times \vec{u}$ is the vorticity [10]. In the present case of two-dimensional motion with negligible inertia forces, it is convenient to introduce a stream function Ψ so that the conservation of mass equation is satisfied identically and the single non-zero component of vorticity becomes $\omega = -\nabla^2 \Psi$

$$\text{then } \nabla^2 (\nabla \times \vec{u}) = 0 \text{ becomes } \nabla^2 (\nabla^2 \psi) = 0 \quad (7)$$

The Raleigh number (Ra) denotes the ratio of buoyant to viscous forces.

$$Ra = (g\beta TL^3)/(\eta\rho^{-1}K CL^{-1}) \quad (8)$$

Here, η is dynamical viscosity L is the length of the system.

4. Mesh Generation

The quality of the grid plays a direct role on the quality of the analysis, regardless of the flow solver used. Additionally, the solver is more robust and efficient when using a well constructed mesh. Triangular grids (T-grids) were generated for in this numerical analysis for considered molten system. Figure 2 shows the mesh generated of molten silicon domain in DS furnace. Boundary conditions used in heat transfer computations are specified at the boundaries of the computational domain. A numerical method based on an adaptive mesh refinement discretization exhibits a computationally efficient technique to solve the transport process of conservation equations like mass, momentum, energy etc, describing the evolution and dynamics of thermal boundaries.

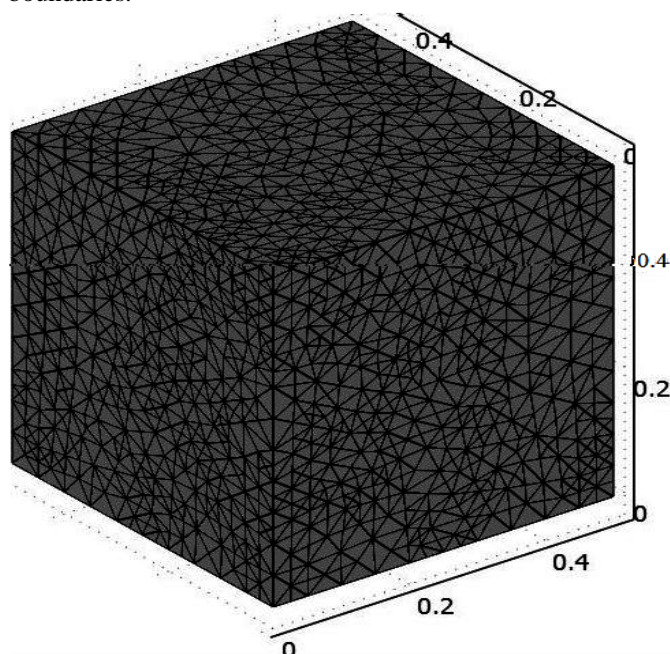


Figure 2: Mesh Generation for melt domain in DS system using finite element method

The governing equations and the boundary conditions for the melt flow and heat transfer characteristics in the molten Si system are solved numerically using finite element method in

which the calculation domain is discretized as triangular element into a finite number of elements. The mesh nodes are between 87954 and 119087 for considered system. The computations are performed using the three-dimensional (3D) axis-symmetry hypothesis for molten silicon of rectangular-shaped silica crucible. The time-independent, Newtonian, incompressible Navier-Stokes model for fluid flow, heat and mass transfer, along with weak form of the boundary is solved using the finite-element numerical technique. By default, the conditions of zero velocities (Wall boundary conditions) are used at the solid-gas boundaries.

5. Simulation Results and Discussion

The numerical simulations of molten Si flow properties such as stream line flow, Peclet numbers Reynolds numbers, convective and conductive heat flux, vorticity generations were carried out using finite element method for the various Rayleigh numbers. In this paper, we have focused only on the vorticity generation of molten silicon for the three Rayleigh numbers (10, 1000 and 100000) with constant temperature difference 10K at constant Prandtl number $Pr = 0.01$. Vorticity [11] is main physical phenomenon during directional solidification of mc-Si growth. Apart from the velocity field and temperature distribution, the vorticity generation is possible during melt crystal growth process. It could be controlled by rotating crucible or applying the magnetic field on the melt flow. Vorticity is related with the linear integrals of the velocity. From the obtained simulation results, there are two types of vorticities generated. One is primary vorticity at central melt regime, other one is secondary vorticity at periphery melt region which are shown in figure 3.

Figure 3(a) shows that the primary vorticity occupied most of the melt region with very low vorticity values, below 30(1/s), for low Raleigh number $Ra = 10$. At the same time, the secondary vorticities are formed only in very small region. So, the melt flow fluctuation may not be much for this Rayleigh number. Figure 3(b) displays that the primary vorticity is dominated at central region compared to the secondary vorticities of periphery region of melt domain at Rayleigh number $Ra = 1000$. It may lead to heavy melt fluctuation and inhomogeneous dopant and impurities distributions in growing crystal. Figure 3(c) shows that secondary vorticities are heavily dominated to compare the primary vorticity with high vorticity values of more than 100(1/s). This has created more perturbation of melt flow during directional solidification growth process. So, we suddenly need to control using appropriate external force on the melt flow. Otherwise, the growing crystal becomes bad in quality. The Positive value of vorticity corresponds to the melt surface moving upwards and the negative value of vorticity corresponds to the melt surface moving downwards. We conclude from the obtained results that the low Rayleigh number is preferable.

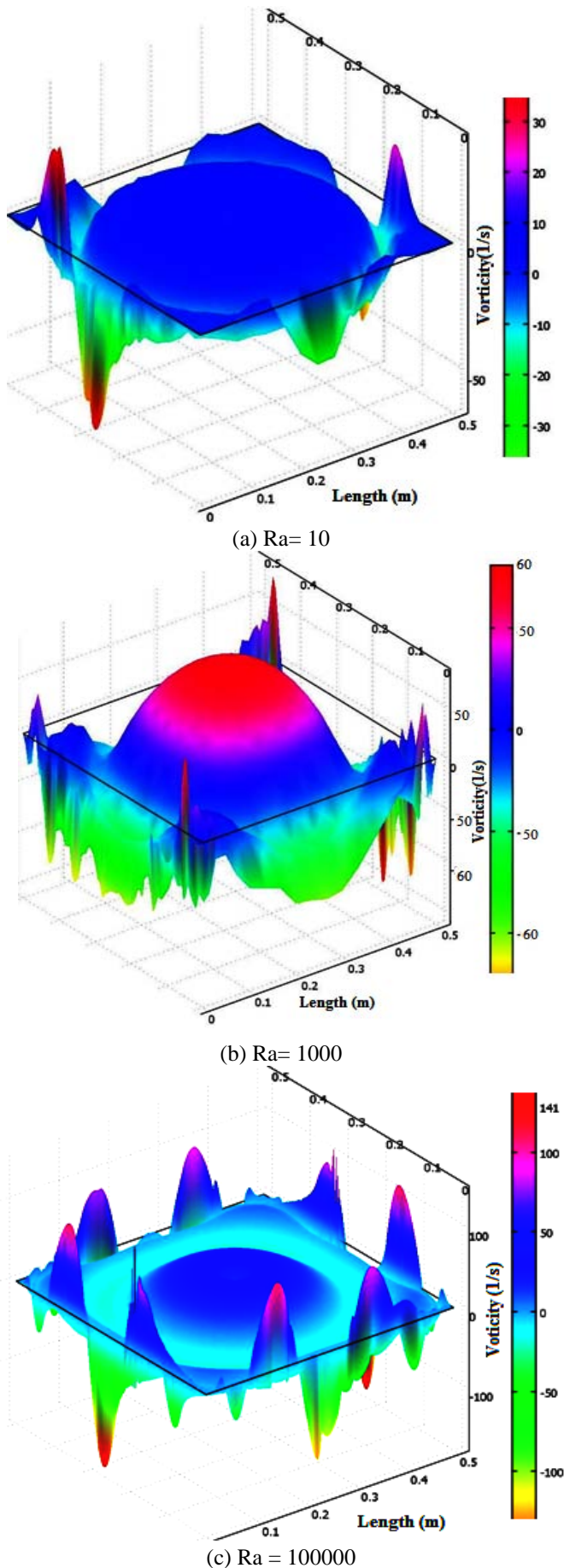


Figure 3: Vorticity generation in molten silicon at various Rayleigh numbers

6. Conclusions

We carried out numerical simulations of heat transfer and fluid flow characteristic of mc-Si melt in a directional solidification system for mc-Si ingot growth using finite element technique. A stationary model of the framework has been made using incompressible Newtonian fluid flow of Navier-Stokes equation in the Boussinesq approximation and the convection-conduction equation. Our objective in the present work was to study the convective flows induced by a temperature gradient and understanding the fluid mechanism for various Rayleigh numbers during multi-crystalline silicon crystal growth process for PV application. Vorticity generation study is essential to control the melt flow fluctuations. We have studied the vorticity generation of the melt flow due to buoyancy effect in silicon fluids. The present study is focused on the influence of Rayleigh numbers. The Rayleigh numbers ranging between $10 < Ra < 10000000$, are simulated at constant Prandtl number (0.01) and the results are given in the present paper only for $Ra=10$, $Ra=1000$ and $Ra=1000000$. The computed results reveal that dimensionless numbers should be incorporated with silicon melt growth of directional solidification process.

References

- [1] A.F.B. Braga, S.P. Moreira, P.R. Zamperi, J.M.G. Bacchin, P.R. Mei, "New processes for the production of solar-grade polycrystalline silicon": A review, *Solar energy materials and solar cells*, 92, pp. 418-424, 2008.
- [2] R.Ronit, Prakash et al, "Grain growth of cast multicrystalline silicon grown from small randomly oriented seed crystal", *Journal of Crystal Growth*, 401, pp.717-71, 2014.
- [3] JJ.Xu, "Introduction to stability and dynamics of interface in solidification", Beijing: Science Press, 2006.
- [4] Balaji Devulapalli and S.Milind, Kulkarni, "Modeling multi-Crystalline Silicon Growth in Directional Solidification Systems", *ECS Transactions*, 18 (1), pp. 1023-1029, 2009.
- [5] Qisheng Chen, Yanni Jiang, Junyi Yan, Ming Qin, "Progress in modeling of fluid flows in crystal growth Processes", *Progress in Natural Science*, 18, pp.1465-1473, 2008.
- [6] Jeffrey J. Derby, James R. Chelikowsky et al, "Large-scale numerical modeling of melt and solution crystal growth", *AIP Conf. Proc.* 916, 139, 2007.
- [7] M.Srinivasan. & P.Ramasamy, " Modeling of physical phenomena on Si melt during crystal growth process by Directional solidification method", *International journal of Chem Tech Research*, 6, pp.1585-1587, 2014. .
- [8] G.De Vahl Davis and I P. Jones, " Natural convection in a square cavity" —a comparison exercise, *Int. J. Num. Meth. in Fluids*, 3, 227-24, 1983.
- [9] Keshra Sangwal, "Elementary crystal growth", SAAN publications, Lublin, 1994.
- [10] L. Braescu, and T. F. George , "Critical Marangoni numbers and their effect on the dopant distribution in silicon fibers", *Int. Jou.of .Math Models and Methos in Applied Sciences*, Issue 3, Volume 2, 2008.
- [11] D. Schwabe, et.al "Studies of Marangoni Convection in Floating Zone", *Actn Astronautica* Vol. 9, No. 3, pp. 183-186, 1982.

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