Journal of Crystal Growth 484 (2018) 78–85

Contents lists available at ScienceDirect

Journal of Crystal Growth

journal homepage: www.elsevier.com/locate/crys

Numerical study of melt flow under the influence of heater-generating magnetic field during directional solidification of silicon ingots

Zaoyang Li [a,b,*], Xiaofang Qi [a], Lijun Liu [a], Genshu Zhou [b]

[a] School of Energy and Power Engineering, Xi'an Jiaotong University, Xi'an, Shaanxi 710049, China
[b] State Key Laboratory for Mechanical Behavior of Materials, Xi'an Jiaotong University, Xi'an, Shaanxi 710049, China

ARTICLE INFO

Article history:
Received 1 October 2017
Received in revised form 18 December 2017
Accepted 21 December 2017
Available online 27 December 2017
Communicated by J.J. Derby

Keywords:
A1. Computer simulation
A1. Fluid flows
A1. Magnetic fields
A1. Directional solidification
B2. Silicon

ABSTRACT

The alternating current (AC) in the resistance heater for generating heating power can induce a magnetic field in the silicon melt during directional solidification (DS) of silicon ingots. We numerically study the influence of such a heater-generating magnetic field on the silicon melt flow and temperature distribution in an industrial DS process. 3D simulations are carried out to calculate the Lorentz force distribution as well as the melt flow and heat transfer in the entire DS furnace. The pattern and intensity of silicon melt flow as well as the temperature distribution are compared for cases with and without Lorentz force. The results show that the Lorentz force induced by the heater-generating magnetic field is mainly distributed near the top and side surfaces of the silicon melt. The melt flow and temperature distribution, especially those in the upper part of the silicon region, can be influenced significantly by the magnetic field.

1. Introduction

The photovoltaics (PV) industry is growing fast, which is evidenced by the data that the compound annual growth rate of PV installation was 42% during the past 15 years [1] and the cumulative PV capacity installed worldwide exceeded 300 GWp by 2016 [2]. Silicon ingot manufactured by directional solidification (DS) method is the main material for solar cells and the market share is more than 60% [2]. Therefore, it's essential to study the DS process and improve the silicon ingot quality for promoting the development of PV industry. The DS is a highly coupled nonlinear thermal process with complex interactions among the silicon melt flow, argon flow and different solid components [3]. In particular, the silicon melt flow can influence the temperature distribution, impurities transport and crystallization interface shape significantly [4,5]. Therefore, a deep and comprehensive understanding of the melt flow characteristics is crucial for optimization and control of the DS process.

Some researchers carried out global or local simulations of heat transfer and fluid flow in the DS furnace to study the influence of growth parameters on silicon melt flow [5–8]. The thermal buoyancy force is considered as the main driving force for the melt flow in these studies. In order to actively control the melt flow, some researchers designed various magnetic fields and studied the influence of Lorentz forces on flow pattern and intensity. For example, Vizman et al. [9,10] numerically studied the 3D silicon melt flow in the DS of silicon ingots with different types of magnetic fields, including vertical magnetic field (VMF), horizontal magnetic field (HMF) and traveling magnetic field (TMF). Li et al. [11] experimentally studied the effect of alternating magnetic field (AMF) on the melt flow, which can influence the removal of metal impurities in silicon ingots. In order to apply the magnetic field conveniently, Rudolph et al. [12,13] developed a heater-magnet module that can generate heating power and a TMF in the crystal growth furnace simultaneously. Dropka et al. [14] studied the influence of such a TMF on silicon melt flow and crystallization interface shape in a DS furnace. The above studies show that the Lorentz force induced by an appropriate magnetic field can suppress the thermal buoyancy force, control the silicon melt flow and influence the DS process.

In the general industrial DS furnace with resistance heating [5,15], an external magnetic field is rarely applied to control the silicon melt flow due to high cost and complex design. However, the alternating current (AC) in the heater for generating heating power can induce an internal magnetic field. This kind of heater-generating magnetic field exists in the general industrial DS process and is not specially designed, which is different from the above-mentioned TMF generated by the specially designed

---

* Corresponding author at: School of Energy and Power Engineering, Xi'an Jiaotong University, Xi'an, Shaanxi 710049, China.

E-mail address: lizaoyang@mail.xjtu.edu.cn (Z. Li).

https://doi.org/10.1016/j.jcrysgro.2017.12.033
0022-0248/© 2017 Elsevier B.V. All rights reserved.

heater-magnet module [12–14]. The heater-generating magnetic field may influence the melt flow and crystal growth significantly, whereas little research has been devoted to this topic. Therefore, we carry out 3D global numerical simulations in this paper to study the distribution of Lorentz force induced by the heater-generating magnetic field as well as its influence on silicon melt flow, temperature distribution and other crystal growth parameters in an industrial DS furnace.

2. Model description

The configuration and dimensions of the DS furnace for casting silicon ingots have been introduced in a previous study [15]. The furnace includes silicon region, quartz crucible, graphite susceptors, graphite heater, carbon felt insulations and other components. The physical properties of all these component materials can be found in Table 1 and Ref. [15]. Fig. 1 shows the schematic diagrams of the core parts in the DS furnace including silicon melt and graphite heater. The volume of the cuboid silicon melt region is $0.84 \times 0.84 \times 0.26\ \mathrm{m}^3$, and therefore the finally solidified silicon ingot is about 450 kg. A snakelike graphite heater is around the silicon region and three electrodes labeled with A, B and C are connected to it. A three-phase AC is connected to the three electrodes to generate heating power in the graphite heater. It's obvious that the three-phase AC is in delta connection, as shown in Fig. 1(c). The expressions of the three-phase AC in this study are:

$$I_A = 1742\sin(100\pi t), \tag{1}$$

$$I_B = 1742\sin(100\pi t + 2\pi/3), \tag{2}$$

$$I_C = 1742\sin(100\pi t + 4\pi/3). \tag{3}$$

The above equations indicate that the current amplitude is 1742 A, the angular frequency is 100π, the frequency is 50 Hz and the phase difference is 120°. The three-phase AC can generate a total heating power of 56 kW to guarantee that the temperature at the silicon bottom is higher than the melting point of 1685 K and the silicon feedstock is fully melted. At the same time, a non-steady magnetic field arises due to the phase shift between the three delta-connected heater segments, as shown in Fig. 1(c). The heater-generating magnetic field can induce Lorentz force in the silicon melt and may influence the flow pattern and intensity.

As the frequency of the magnetic field is much higher than that of the silicon melt flow, the periodic Lorentz force can be averaged over one time period. The software ANSYS Maxwell is applied to calculate the distributions of magnetic field and Lorentz force in the silicon melt. To guarantee that the software is used correctly and the numerical method is appropriate, the generation of a TMF is first solved according to a previous study [16]. The results show that the Lorentz force calculated by Maxwell is in good agreement with that in this reference. For the accurate calculation of 3D magnetic field in this study, the adaptive mesh refinement and skin depth meshing techniques are applied, and the number of the final mesh is about 920,000.

Table 1
Physical properties for silicon melt and graphite heater.

Material	Variable	Value
Silicon	Density ($\mathrm{kg/m^3}$)	2530
	Specific heat (J/kg·K)	900
	Thermal conductivity (W/m·K)	64
	Dynamic viscosity (kg/m·s)	7×10^{-4}
	Thermal expansion coefficient (1/K)	1.36×10^{-4}
	Melting point (K)	1685
	Emissivity	0.3
	Electrical conductivity (S/m)	1×10^{6}
	Relative magnetic permeability	1
Graphite	Density ($\mathrm{kg/m^3}$)	1830
	Specific heat (J/kg·K)	1800
	Thermal conductivity (W/m·K)	100
	Emissivity	0.8
	Electrical conductivity (S/m)	1×10^{5}

To study the influence of magnetic field on silicon melt flow, the 3D global simulations of fluid flow and heat transfer in the entire DS furnace are carried out. The simulations include silicon melt flow, argon gas flow, solid thermal conduction and thermal radiation. In silicon melt, the Boussinesq approximation is applied to describe the thermal buoyancy force due to density change. Therefore, the governing equations for melt flow are:

$$\nabla \cdot \vec{u} = 0, \tag{4}$$

$$\rho\frac{\partial \vec{u}}{\partial t} + \rho\,\vec{u}\cdot\nabla\vec{u} = -\nabla p + \nabla\cdot[\mu(\nabla\vec{u} + \nabla\vec{u}^T)] - \rho\,\vec{g}\,\beta_T(T - T_{ref}) + \vec{F}_L, \tag{5}$$

$$\rho C_p\frac{\partial T}{\partial t} + \rho C_p\,\vec{u}\cdot\nabla T = \lambda\nabla\cdot(\nabla T), \tag{6}$$

where $\vec{u}$ is the velocity, ρ is the density, t is the time, p is the pressure, μ is the dynamic viscosity, $\vec{g}$ is the gravity acceleration vector, β_T is the thermal expansion coefficient, T is the temperature, T_{ref} is the reference temperature and C_p is the specific heat capacity. $\vec{F}_L$ is the time-averaged density of Lorentz force induced by the heater-generating magnetic field.

For the boundary condition settings, the temperature continuity and heat flux conservation are kept at all interior boundaries between any two different computational domains. No-slip condition is applied at all solid walls in the argon gas and silicon melt domains. Along the melt free surface, both the normal velocity component and the shear stress are set to zero. In the DS process for silicon ingots, the isotherms in the silicon melt are usually flat and the radial temperature gradient along the melt free surface is small [10]. This means the Marangoni force is very weak and its influence on melt flow is limited to the region near the free surface [10]. Therefore, the Marangoni force is not important in the case discussed in this paper and it's neglected in this study to make clear analyses of the effects of Lorentz force. The temperature of the furnace outer wall is assumed to 300 K, and the inlet temperature and pressure of argon gas are set to 300 K and 60,000 Pa, respectively. A total mesh number of 2,300,000 is applied for the entire DS furnace, and the mesh number for silicon melt region is 384,000. The above 3D numerical model for fluid flow and heat transfer in the DS furnace is established by using the software ANSYS Fluent, and it has been validated by comparing the numerical results with the experimental data [17].

3. Results and discussion

3.1. Lorentz force density

To study the influence of heater-generating magnetic field on silicon melt flow and other crystal growth parameters, the distributions of Lorentz force density are first calculated. Fig. 2 shows several isosurfaces of the magnitude of Lorentz force density $|\vec{F}_L|$ in silicon melt. The expression of $|\vec{F}_L|$ is:

$$|\vec{F}_L| = \sqrt{\vec{F}_X^2 + \vec{F}_Y^2 + \vec{F}_Z^2}, \tag{7}$$

where $\vec{F}_X$, $\vec{F}_Y$ and $\vec{F}_Z$ are the vector components of Lorentz force density in X, Y and Z directions, respectively. The maximum value