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Preliminary study on molten silicon velocity distribution during the directional solidification into *i*-DSS furnace

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Abstract

The *induction* Directional Solidification System (*i*-DSS) is a furnace designed to cast solar grade silicon ingots that makes use of induction heating in the Directional Solidification process for the production of multi-crystal silicon. The isostatic graphite, that envelopes the quartz crucible where the silicon is melted, is heated by induction, so in *i*-DSS the isostatic graphite acts as susceptor.

The Alternative Magnetic Field (AMF), which frequency and intensity have been chosen in order to maximize the efficiency of the heating, is not completely shielded by the graphite and it affects the flow of silicon fluid. In this paper, the fluid motion is investigated taking into account various position of the solidification front.

The study is applied to the lab-scale *i*-DSS installed at Laboratory of Electroheat (LEP) of University of Padova.

The electromagnetic and fluid problems have been studied by numerical models developed using the commercial FEM code COMSOL Multiphysics.

Key words : Coupled problems, Directional Solidification System, Silicon Casting, mc-silicon.

Introduction

The peculiarity of *induction* directional solidification system is the introduction of this heating technique in the silicon casting. Among other advantages, induction heating allows better control of the process [1].

The heating system is composed by three different inductors, each one independently fed by its respective resonant capacitor bank and IGBT converter.

The aim of this study is to evaluate if the electromagnetic field, produced by the side coil, has some influence on the patterns of molten silicon flow. The EM field produced by the side coil has been designed to maximize the power induced in the lateral susceptors and not for controlling the flow motion. Furthermore, the EM field is strongly shielded by susceptors at the working frequency and the field amplitude is relative low in the silicon.

A simple Computational Fluid Dynamics (CFD) study, based on the classical $k-\epsilon$ model, has been developed to predict the motion of fluid silicon. The model takes into account the buoyancy force and the influence of AMF.

The study is applied to the lab-scale of *i*-DSS realized to University of Padua. The furnace is able to cast squared ingots up to 120 kg of silicon load.

The lab-scale *i*-DSS

The hot-zone of the *i*-DSS is very similar to the ones of standard DS furnace, fig.1. In fact, the hot-zone of *i*-DSS comprises the same isostatic graphite plates that contain the commercial quartz crucible like a box. The thermal insulator elements, made of graphite felts, are located to envelope the graphite box and to cover the top susceptor. The bottom graphite plate is not insulated in order to guarantee the thermal flux required to obtain a directional solidification.

Three different inductors, namely the bottom, side and upper inductor, are positioned as shown in Fig.1. Each inductor has been designed to heat the corresponding susceptor realized with isostatic graphite plates under and positioned closed to the inductor itself. The different positions of each heating source guarantee an accurate control of the temperature field inside the hot zone during all the process phases.

In order to maximize the energy efficiency of the process, the thickness of the lateral insulating graphite has been chosen in order to guarantee an appropriate balance between thermal losses and inductor efficiency. The thickness of graphite felts has an obvious impact on the insulation, but an increasing thickness has also a negative impact on the inductor efficiency. Due to significant distance between the bottom and top inductors from the melt, the AMF generated by these two inductors is negligible in the silicon.

On the contrary, the electromagnetic field generated by the lateral inductor is not negligible inside the molten silicon. The influence of AMF produced by the side inductor on fluid flow has been investigated in this work.

The simulation model

In order to solve a Navier-Stokes equation for the Newtonian fluid during the solidification process 2D axisymmetric models of the furnace have been developed.

The Navier-Stokes equation for Newtonian fluid in vectorial forms can be formulated as follow:

$$\rho \left[\frac{\partial \vec{u}}{\partial t} + (\vec{u} \cdot \nabla) \vec{u} \right] = -\text{grad } p + \eta \Delta \vec{u} + \vec{F} \quad (1)$$

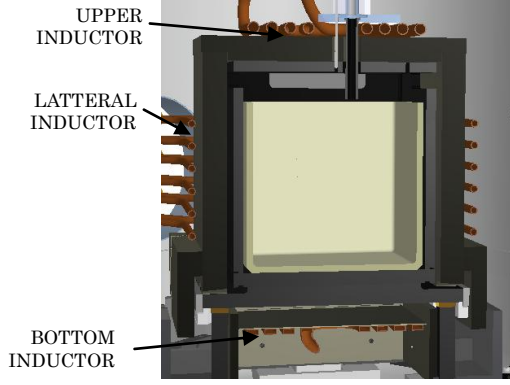


Fig. 1: Sketch of the lab-scale of *i*-DSS furnace.

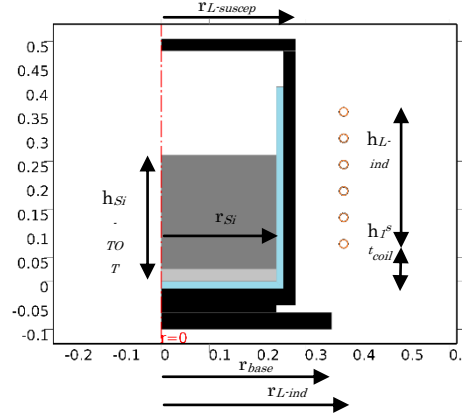


Fig. 2: 2D axisymmetric model with lateral inductor.

with: ρ density of molten silicon, \vec{u} velocity vector, p pressure, η viscosity terms and body force \vec{F} .

The body force, in our case, is composed by Lorentz forces (\vec{F}_L), buoyancy forces (\vec{F}_{Buoy}) and Marangoni effect (\vec{F}_M).

For a liquid metal, like silicon, whose density and energy surface depend linearly from temperature, the \vec{F}_{Buoy} under gravitational field and the Marangoni effect could be formulated respectively as:

$$\vec{F}_{Buoy} = \rho(T)\vec{g} = \rho_0[1 - \beta(T - T_{ref})]\vec{g} \quad (2)$$

$$\vec{\sigma}_\tau = M_a \cdot \text{grad}_\tau T \quad (3)$$

The linear thermal expansion is indicated as β , M_a is the coefficient of surface tension variation with temperature.

The time harmonic problem has been solved by means of magnetic vector potential formulation, so the \vec{F}_L , in a generic point C, can be described as:

$$\vec{F}_L(t) = \vec{j}_{Cre} \times \vec{B}_{Cre} \cos^2 \omega t + \vec{j}_{Clm} \times \vec{B}_{Clm} \sin^2 \omega t - (\vec{j}_{Cre} \times \vec{B}_{Clm} + \vec{j}_{Clm} \times \vec{B}_{Cre}) \frac{\sin 2\omega t}{2} \quad (4)$$

The viscosity of molten silicon and the resonant frequency of inductor, above 2 kHz, allow, in first approximation, to neglect the time dependent component of Lorentz Force. In the computational model the only constant component to take into account is:

$$\vec{F}_{Lav} = \frac{\vec{j}_{Cre} \times \vec{B}_{Cre} + \vec{j}_{Clm} \times \vec{B}_{Clm}}{2} \quad (5)$$

To analyze the fluid dynamics, the COMSOL simulation code applies the RANS approach and specifically $K-\varepsilon$ formulation. To facilitate the convergence of the problem, the flow pattern has been initially resolved taking into account only thermal distribution. In a second step, the solely electromagnetic force has been introduced.

All the data in the models have been reported in the Table 1, in accordance with [2].

Table 1: Data implement on computational models

Silicon proprieties						Copper proprieties	Isostatic Graphite proprieties
Density at Temperature reference	Linear Thermal expansion coefficient	Viscosity	Marangoni coefficient	Thermal Conductivity	Electric Conductivity	Electric Conductivity	Electric Conductivity
ρ_0 [Kg/m ³] @ $T_{ref} = 1685$ K	β [K ⁻¹]	η [Pa·s]	Ma [N (m·K) ⁻¹]	K [W (m·K) ⁻¹]	σ_{e-si} [S/m]	σ_{e-Cu} [S/m]	σ_{e-C} [S/m]
2530	1.44 E-4	7.56 E-4	-4 E-4	60.5	1.43 E6	5 E7	8.65 E4

Coefficients of k-ε formulation					Chamber pressure	Frequency	Current
C_{1e}	C_{2e}	C_{1e}	σ_μ	σ_e	p_{cham} [mbar]	f [Hz]	I_{coil} [Arms]
1.44	1.92	0.09	1.0	1.3	600	2000	875

Geometrical dimensions								
r_{Si} [mm]	$r_{L-sucop}$ [mm]	r_{base} [mm]	r_{L-ind} [mm]	h_{si-TOT} [mm]	$h_{si^{st-coil}}$ [mm]	h_{L-ind} [mm]	Φ_{ind} [mm]	t_{Suscep} [mm]
240	280	355	380	263	93	275	20	25

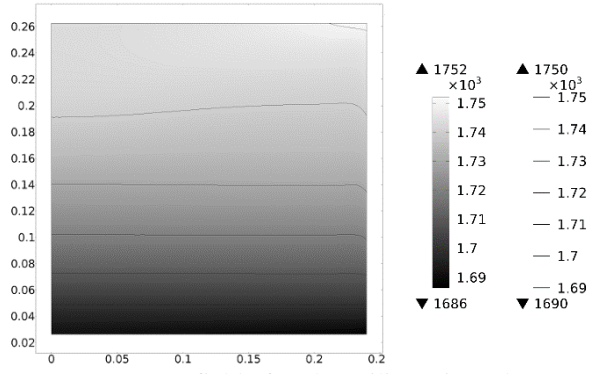


Fig. 3: Temperature field of molten silicon, in K degree.

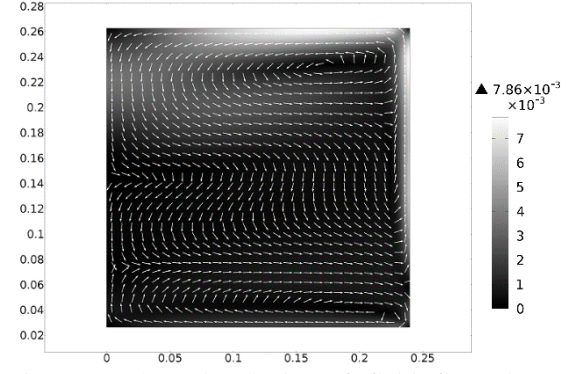


Fig. 4: Path and velocity of fluid flow due to buoyancy force and Marangoni effect.

The simulation results

In the Fig. 3 the temperature field of molten silicon is presented as result from a steady state thermal model in CGSim code.

The distribution of Lorentz force has been solved by Flux model and imported in COMSOL and it is shown in the Fig. 5. The applied magnitude of current, 875 Arms, is the one that transfers to the system the heating power required during solidification. In this condition, the AMF generated, when the solid part is 10% of the total silicon height, has a strong influence on the fluid flow.

The peak of velocity under thermal perturbation is about 13 times lower than the one calculated by imposing Lorentz force. The ratio between the velocities decreases towards the core of molten Silicon, because the skin effect confines the Lorentz force to the external layers of silicon.

The study of the flow pattern has been done taking into account different positions of the solidification surface that corresponds to heights of solid part equal to 30% (Fig.7), 50% (Fig.8), and 70% (Fig.9) of total height of the molten bath.

In the initial steps of solidification, simulations show a pattern with only one main vortex. The velocity near the solid-liquid interphase, where the segregation and precipitation of impurity occur, has a relevant effect to obtaining a high quality ingot. A low velocity near the interphase during the growth has a low mixing effect.

The pattern of flow during the growth evolves in a double vortex, which is the typical structure taken by an electrical conductive fluid inside an ideal infinite solenoidal inductor.

Conclusion

The preliminary models presented in this paper are strongly simplified and make use of K-e model that has several limitations. Nevertheless, they allow a preliminary evaluation of the effects produced by the electromagnetic force generated by the lateral inductor on the fluid flow inside the *i*-DSS furnace. The contribution of Lorentz Force is not negligible on the silicon molten flow and it could have a strong influence in the quality of ingot in terms of defects, like impurity concentration and dislocations.

Taking into account the geometry of *i*-DSS furnace, the use of 3D models is mandatory for achieving more accurate results. The Lorentz force in the molten silicon calculated in 3D model, has a complex 3D distribution as shown in Fig.10.

The real free surface is not considered in these models but its evaluation is necessary to improve the result quality, also because Lorentz Force imposes an electromagnetic pressure on free surface modifying its shape.

The numerical results confirmed the necessity of CFD simulations in order to improve the directional solidification process.

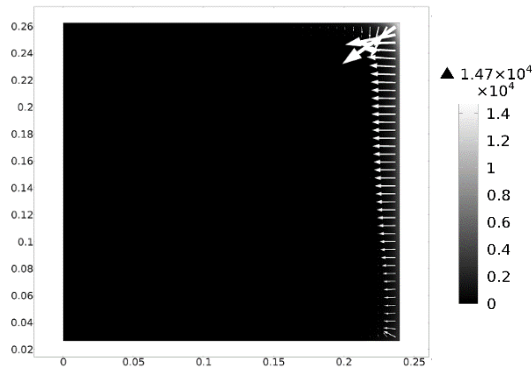


Fig. 5: Map of constant component of Lorentz force, 10% of total silicon height.

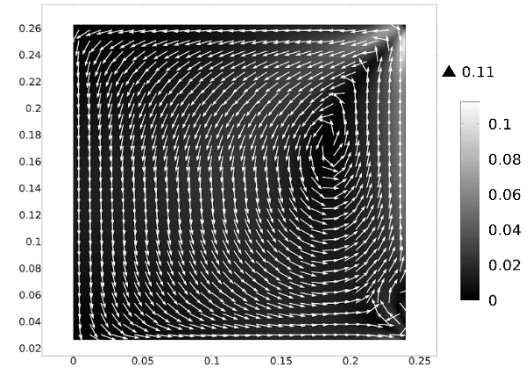


Fig. 6: Path and velocity of fluid flow EMF, 10% of total silicon height.

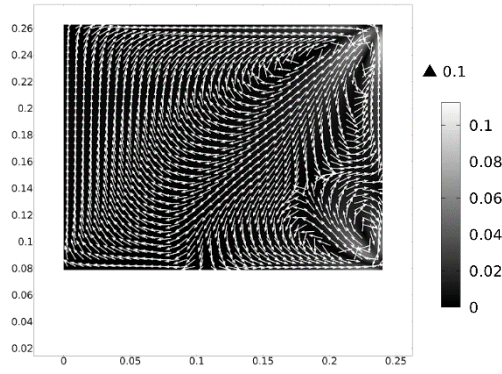


Fig. 7: Maps of Lorentz force constant component, 30% of total silicon height.

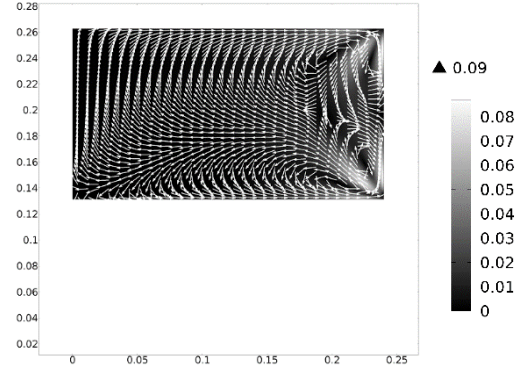


Fig. 8: Path and velocity of fluid flow EMF, 50% of total silicon height.

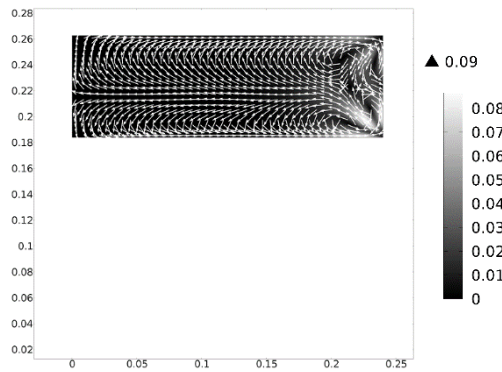


Fig. 9: Maps of Lorentz force constant component, 70% of total silicon height.

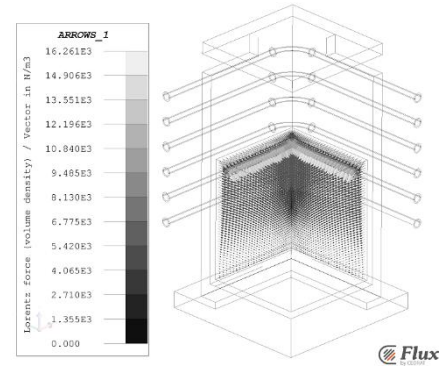


Fig. 10: 3D Vector plot of constant component of Lorentz force

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