FREE SURFACE SHEAR FLOWS INDUCED BY ALTERNATING ELECTROMAGNETIC FORCES AND APPLICATION TO FLOATING ZONE PROCESS

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Proposed session topic: convection

Besides Joulean heating and free surface deformation caused by the Lorentz force normal component, an additional effect resulting from the generation of radio-frequency alternating magnetic fields in the vicinity of electrically conducting liquid components is the creation of a free surface shear flow. This effect is generally undesired, but could be used to improve convection control in some applications – such as the Floating Zone (FZ) or even the Czochralski (CZ) semiconductor crystal growth processes.

Since the low value of the magnetic skin depth is most often the origin of significant numerical difficulties, we have developed a mathematical model of the electromagnetic field distribution in planar and axisymmetric configurations, which provides equivalent magnetic stresses and heat flux to be applied along the conducting free surface. This model is based on using a matched asymptotic expansion technique in order to approximate the electromagnetic field inside the conductors, together with a Finite Element numerical representation of the electromagnetic field outside the conductors. Compared to existing literature, our method presents the advantage of providing a 3rd-order expansion of the electromagnetic field inside the conducting domain, with a very low approximation error. This improvement is of particular importance along high curvature free surface zones. A particular technique is developed in order to take into account the effect of conducting surface edges – such as the crystal-melt-gas tri-junction line in FZ and CZ silicon growth. In the same way, an original asymptotic method is developed to approximate the Lorentz body force and the heat supply generated by induction currents inside the conducting melt by equivalent magnetic stresses and heat flux applied along the melt surface. These boundary conditions are further used to solve the melt flow and heat transfer problem.

As a 1st application, numerical calculations are carried out in order to depict typical flow patterns obtained in an axisymmetric liquid bridge surrounded by inductors in a micro-gravity environment. The choice of an appropriate inductor shape, and the use of several out-of-phase induction components, allows us to equalize the orders of magnitude of tangential electromagnetic and thermocapillary forces. In such case, the electromagnetic field can be used to counteract the Marangoni effect and to control the flow.

As a 2nd application, our technique is applied to melt flow simulation in the FZ silicon growth process. Detailed analysis of the influence of the electromagnetic tangential force

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on the flow is performed in the vicinity of the tri-junction – which plays a critical role in the solidification process. A typical comparison between results obtained with or without taking this tangential force into account is shown in Fig. 1, thereby illustrating the importance of the electromagnetic shear effect on the flow.

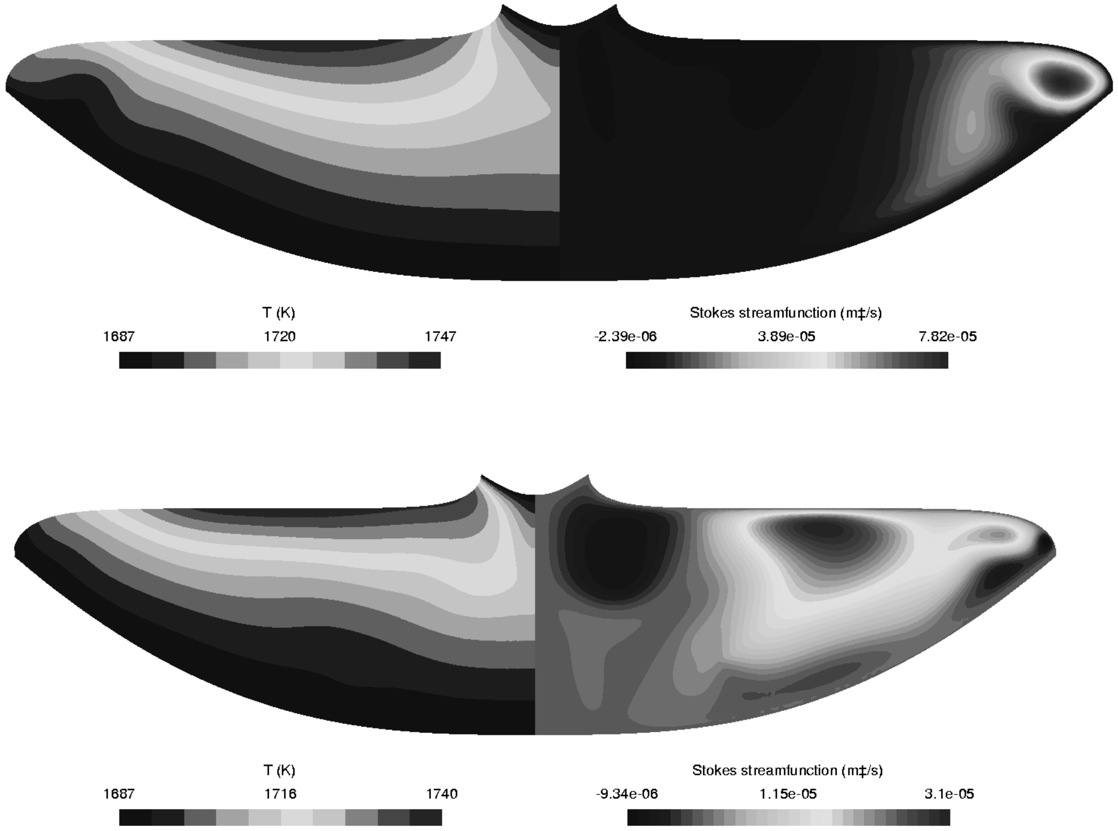

Fig 1: Temperature field (left) and Stokes streamfunction (right) in the melt without (top) and with (bottom) magnetic equivalent tangential force. $Re_{poly}=7460$, $Re_{crystal}=3730$, $Pe=261$, $Gr=2.7\times10^{7}$, *and* $Ma=6116$.

References:

[1] F. Bioul and F. Dupret, 2005, IEEE Trans. Magn. **41** N° 9, 2496 (2005).
[2] F. Bioul and F. Dupret, 2005, IEEE Trans. Magn. **41** N° 9, 2506 (2005).
[3] F. Bioul and F. Dupret, 2005, to be published in J. Non-Equilibrium Thermodynamics, in press.
[4] T. Munakata, S. Someya, and I. Tanasawa, J. Crystal Growth, vol. 235, pp. 167-172, 2002.
[5] J. Bohm, A. Lüdge, and W. Schröder, in: Handbook of Crystal Growth, vol. 2a, ch. 4, Ed. D.T.J. Hurle, North-Holland 1994, p. 213.
[6] F. Dupret and N. Van den Bogaert, in: Handbook of Crystal Growth, vol. 2b, ch. 15, Ed. D.T.J. Hurle, North-Holland 1994, p. 875.
[7] G. Ratnieks, A. Muiznieks, and A. Mühlbauer, J. Crystal Growth **255**, 227 (2003).