FREE SURFACE SHEAR FLOWS INDUCED BY ALTERNATING ELECTROMAGNETIC FORCES. APPLICATION TO LIQUID BRIDGES IN MICRO-GRAVITY AND TO FLOATING ZONE PROCESS

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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 Czochralski or Floating Zone semiconductor crystal growth process for example.

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 forces 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 3^{rd}-order expansion of the electromagnetic field inside the conductors, 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 Czochralski and Floating Zone silicon growth.

As a first application, numerical calculations of the convection induced by electromagnetic and thermocapillary forces 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 Marangoni forces. In such case, the electromagnetic field can be used to counteract the Marangoni effect and to control the flow.

As a second application, our technique is applied to melt flow simulation in the Floating Zone silicon growth process. Detailed analysis of the effect of the electromagnetic tangential force on the flow is performed in the vicinity of the tri-junction – which plays a critical role in the solidification process.