TEMHD Effects On Solidification Under Microgravtiy Conditions

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Abstract

An unexplored potential exists to control microstructure evolution through the use of external DC magnetic fields. Thermoelectric currents form during solidification and interact with this external field to drive microscopic fluid dynamics within the inter-dendritic region. The convective heat and mass transport can lead to profound changes on the dendritic structure. In this paper the effect of high magnetic fields is demonstrated through the use of both 3-dimensional and 2-dimensional numerical models. The results show that the application of a magnetic field causes significant disruption to the dendritic morphology. Investigation into the underlying mechanism gives initial indicators of how external magnetic fields can either lead to unexpected growth behaviour, or alternatively can be used to control the evolution of microstructure in undercooled melts as encountered in levitated droplet solidification

Introduction

Levitation/confinement is often achieved through the combined use of both AC and DC magnetic fields [8]. Under these conditions it is possible to undercool the droplet into a metastable state, where the droplet is still liquid but its temperature is below the solidus temperature. Upon nucleation, rapid dendritic solidification occurs. These conditions are of scientific interest; to understand the fundamental behaviour of solidification in both pure materials and alloys. A common addition is to apply a high DC magnetic field to damp macroscopic fluid flow and create a purely diffusion driven situation. However under certain conditions this magnetic field will interact with microscopic thermoelectric currents that are a natural and inherent part of solidification; generating a Lorentz force and driving microscopic fluid flow. This fluid flow can be sufficient to disturb the heat and solute boundary layers significantly altering the solidification process. In the absence of gravity a weak AC field can be used purely for positioning, while the DC field can be chosen to be significantly large to interact with the thermoelectric currents. The focus of this work is to explore what effect this may have and to provide the first study of how this phenomenon will affect droplet solidification. To do this a dimensionless 3D enthalpy based model is used and scaled to represent an AlSi hypo-eutetic alloy.

Theory

The Seebeck effect [1] describes how an e.m.f ($\Delta\Psi$) forms when two materials with varying Seebeck coefficients (S) are placed in thermal contact and that at the boundary this e.m.f varies with the surface temperature. The generalised form of Ohm's law includes a contribution from the Seebeck effect.

$$\mathbf{J} = \sigma \left(\mathbf{E} + \mathbf{u} \times \mathbf{B} - S \nabla T \right) \tag{1}$$

At the interface the potential difference can be written as

$$\Delta \Psi = \Delta S T \tag{2}$$

The evolution of the dendrite morphology is calculated by an enthalpy-based method [2]. The interfacial temperature (T^i) is defined by the Gibbs-Thompson condition

$$T^i = T_m - \frac{\gamma \left(\theta, \phi \right) T_m}{L} \kappa - m \left(C_0 - C_l^i \right) \tag{3}$$

where the second term accounts for local free energy through surface energy anisotropy and curvature and the final term accounts for solute partitioning in binary alloys. This equation leads to a variation in surface temperature and the formation of thermoelectric currents irrespective of an external magnetic field.

Results

Free Growth of a Single Crystal

To understand the mechanism that will lead to morphological changes a simplified situation of a single crystal freely growing in the bulk is considered. Previous work [3–7] has shown that the thermoelectric currents circulate between the cold tips and the hot roots of the crystal. In figure 1 a similar situation can be observed for a developing dendrite. In this example an additional positive curvature exists at the base of each arm near to the root. This is analogous to the formation of a secondary branch and the resulting undercooling gives rise to a relatively higher surface potential and the formation of another current circulation. As a dendrite continues to develop and many secondary branches form, this can have a significant impact on magnitude and direction of the thermoelectric currents. A more in depth description of this effect is presented in [6]; in summary a larger variation in surface temperature (i.e. an increase in hot and cold regions along the interface due to secondary arms) gives a higher average magnitude of $\mathbf{J}$. In the presence of a low magnetic field aligned along the tip in the $+z$-direction, such that $Re \to 0$ and $Pe \to 0$ the growth can be considered to be diffusion driven; giving an idea of the direction and relative magnitude of the fluid flow. The flow is given in figure 2, where circulations form around each of the tips and circulations around the entire dendrite. For the tips tangential to the field a pair of vortices form, passing from the tip, under and over the arm. For the tips parallel to the field the circulation forms around the arm. The highest velocities can be seen in the root of the dendrite, passing over the tangential arms and at the z tips.

As the magnetic field is increased to 10T convective transport becomes important. The incident flow onto the tangential arm perturbs the interface causing secondary growth and a deflection of the tip. This is highlighted in figure 3, showing the transient growth from both an isometric perspective and also the perspective along the magnetic field. The secondary branches have a direct impact on the formation of thermoelectric currents; as the tips evolve from the surface of the arm the local curvature increases resulting in a decrease in the surface temperature and consequently a change of the potential boundary condition. The net effect is the formation of a potential sources (tips) and sinks (local roots) where thermoelectric currents will begin to circulate around the secondary tips. This is highlighted in figure 4, which shows the surface potential. The currents formed from this potential will also interact with the magnetic field producing Lorentz forces and the situation becomes increasingly complex.

Thermoelectric currents also exist in the inter-dendritic region and the 3-dimensional simulation shows that a high velocity can also exist in this region. To highlight this, a cross-section in the x, z plane through the centre of the dendrite is given in figure 5, showing the y component of velocity. The flow between the first secondary branch and the tangential primary arms persists all the way into the root. A second cross section, in the x, y plane and in between these two branches shows the velocity and how it is not simply confined between the two branches, but forms a global circulation. However this is expected due to the rotational symmetry of the problem.

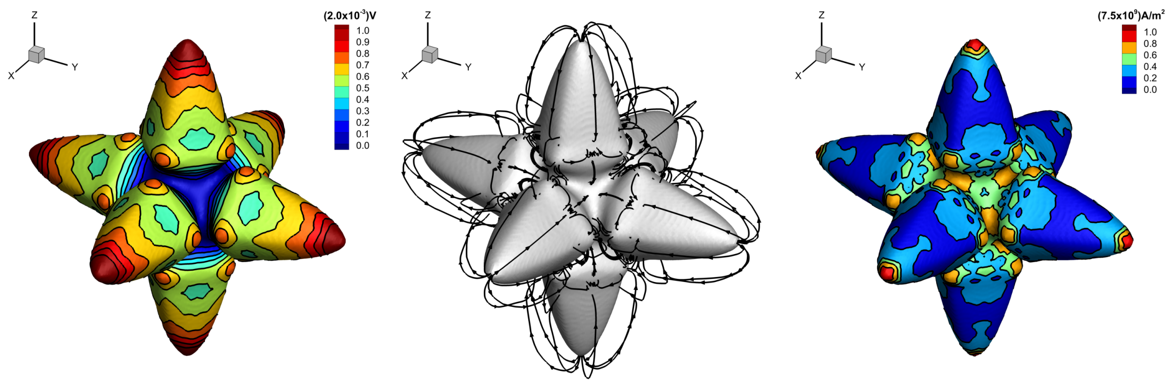

Figure 1: Stagnant growth. Left: Electric potential. Centre: Direction of $\mathbf{J}$. Right: $|\mathbf{J}|$.

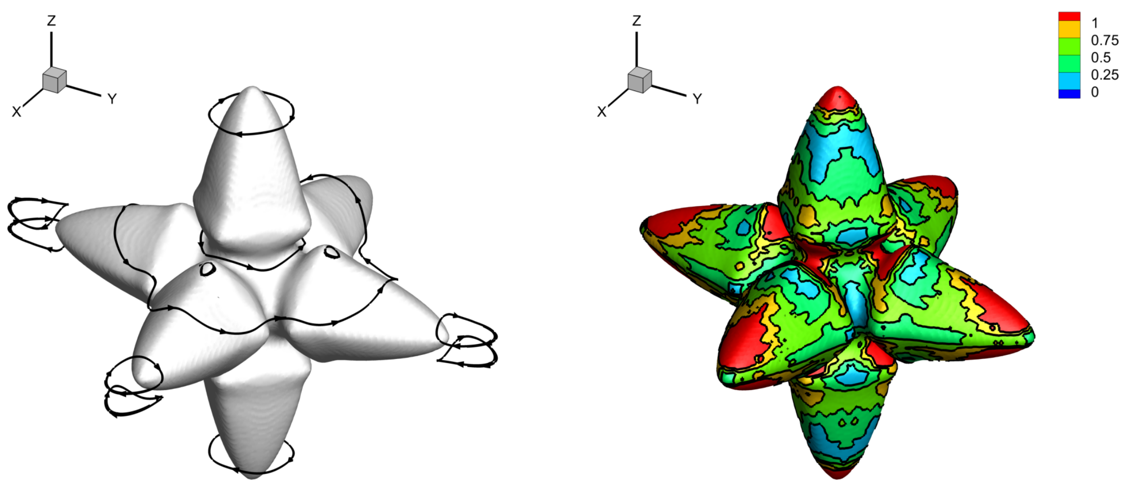

Figure 2: Stagnant growth velocity. Left: Direction of $\mathbf{u}$. Right: Normalised $|\mathbf{u}|$.

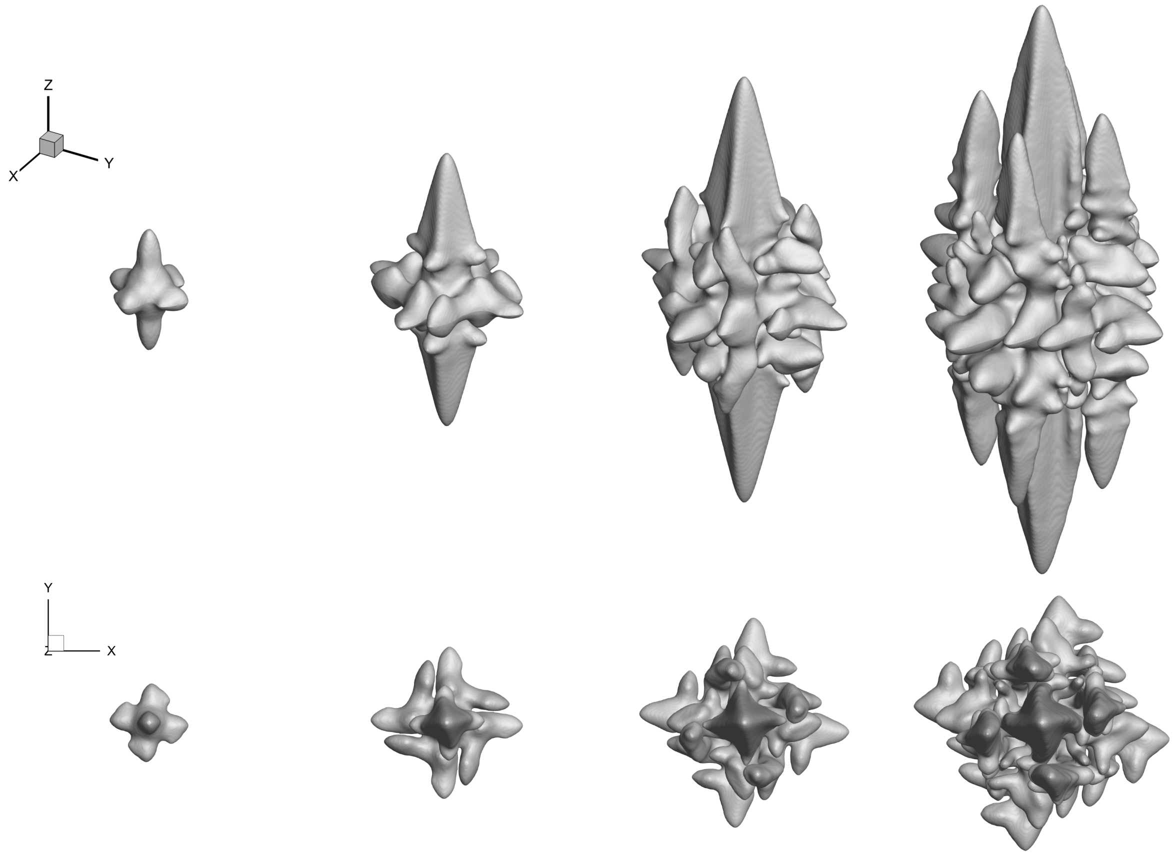

Figure 3: 10T Transient Growth. Top: Isometric perspective. Bottom: Along magnetic field direction.

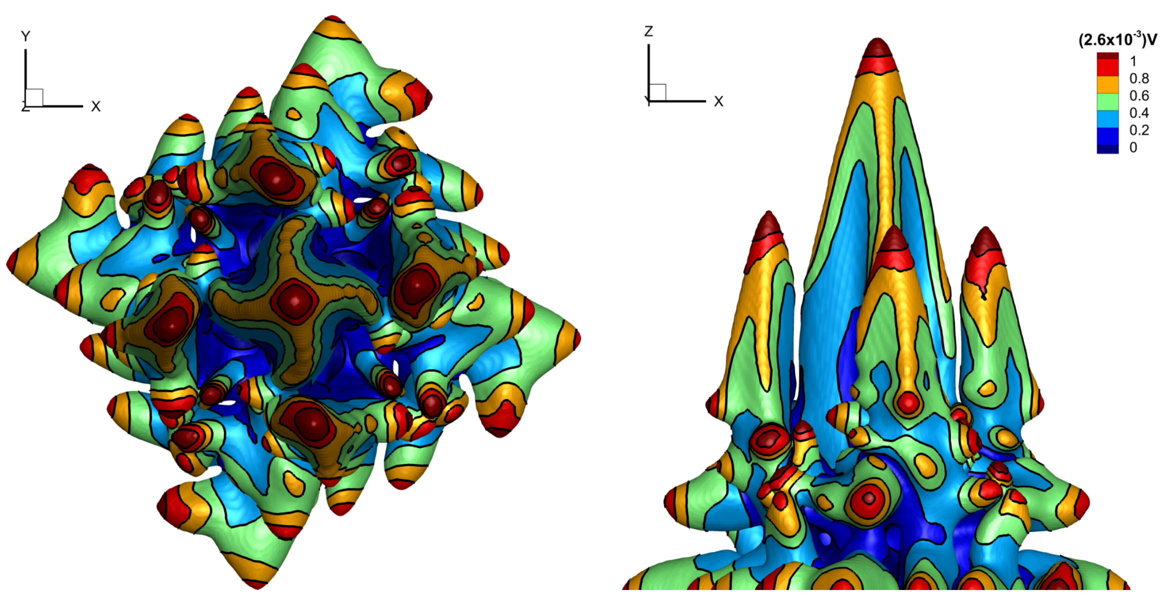

Figure 4: Electric potential of growth in the presence of a 10T magnetic field. Left: x, y plane. Right: x, z plane.

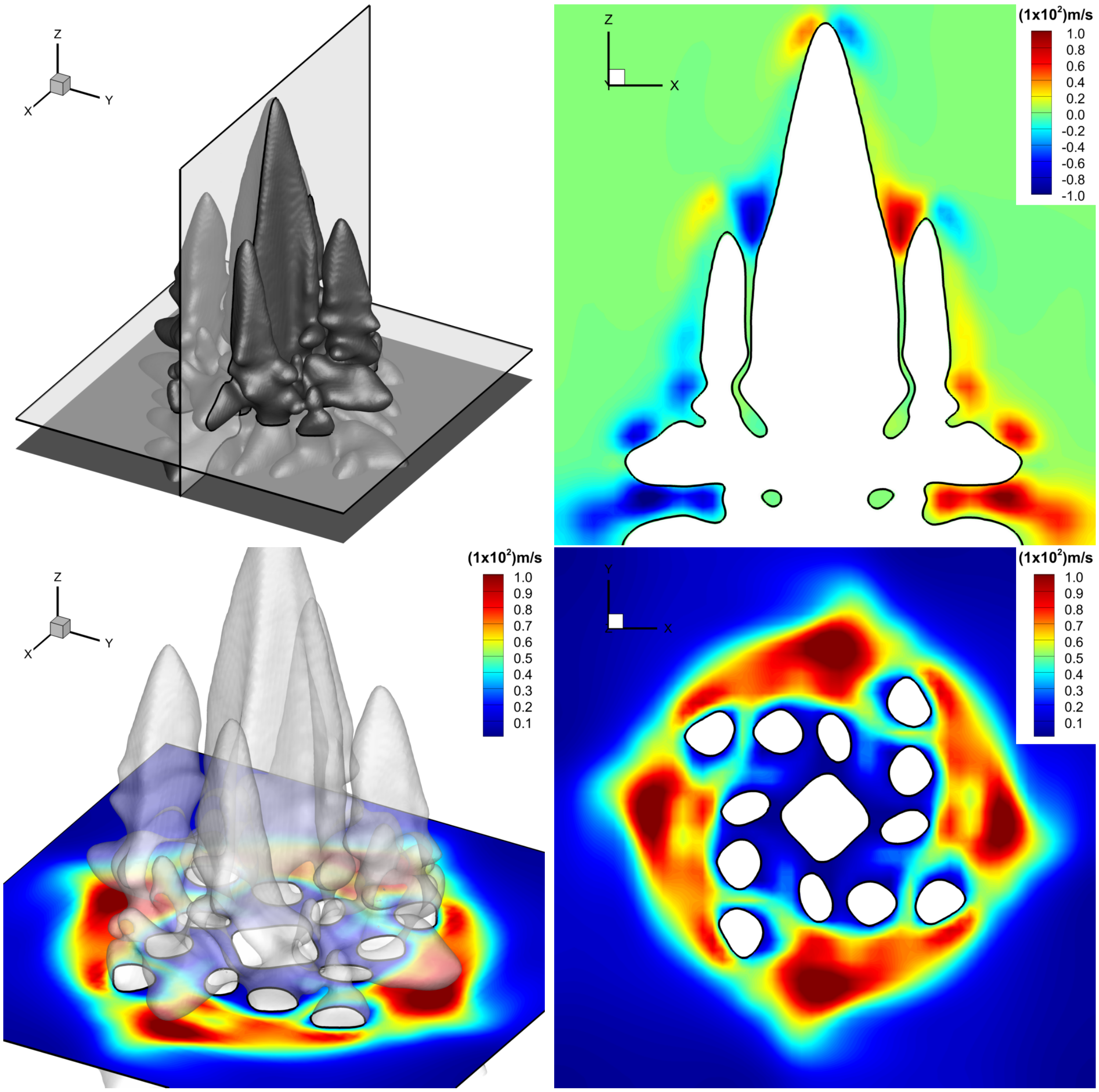

Figure 5: Velocity of growth in a 10T field. Top left: Location of planes. Top right: u_y in the x, z plane. Bottom: $|\mathbf{u}|$ in the x, y plane.

Under microgravity conditions, with no external body forces a droplet of liquid metal will form a spherical equilibrium shape. Consider a droplet with a diameter of 0.4mm. The surface of the droplet is assumed to be adiabatic as the droplet is placed in a vacuum and due to the short duration of solidification heat loss through radiation may be neglected. The droplet begins in a supercooled state and nucleation is triggered on the surface at the positive x pole. Figures 6 and 7 show the evolution of the solidification within the droplet for cases without a magnetic field and with a 10T transverse magnetic field (perpendicular to the plane of growth). In the absence of a magnetic field the dendrite grows statistically symmetric exhibiting 4-fold symmetry. In the case where a magnetic field is present the solidification path takes a preferential route around the surface of the droplet. The change to the morphology is a consequence of the fluid dynamics generated through the interaction of thermoelectric currents and the magnetic field. At the tips of the dendrite the direction of the Lorentz force has the same sense, where each tip forms a clockwise micro circulation of flow. As multiple tips grow these circulations will interact forming a single circulation. The net effect is a larger mesoscopic circulation traversing multiple tips and transporting solute rich fluid downstream of the nucleation site; resulting in a plume of solute ejected from the bulk. The velocity is given in figure 8, where flow that appears to exist within the solid regions has entered a quasi 3-dimensional plane above and below the structure. This is analogous to the inter-dendritic flow of the 3D single crystal shown in figure 5. Figure 9 shows the magnitude of the thermoelectric currents; it is important to note that the normalised scale is logarithmic, highlighting the short range in which these currents act under these conditions. The highest $\mathbf{J}$ is located at the tips growing into the bulk (along the top of the droplet), where micro circulations are perturbing the interface encouraging secondary growth and increasing $\mathbf{J}$. This give a large Lorentz force, but acting over a short distance.

This model suggests two plausible mechanisms. The first is a consideration to the extent of the plume of solute. Through continuity the localised high velocity forces solute into the bulk, however in this region electromagnetic damping becomes dominant and the velocity decreases sharply away from the microstructure. For low magnetic fields, where bulk flow can be significant the extent of this plume is governed by the inertia generated by the Lorentz force and the time for the flow to accelerate under a lower driving force. Ultimately this could lead to macro segregation, while for high magnetic fields the effect is limited to micro segregation. The second mechanism is a change to the inter-dendritic structure. Consider an inter-dendritic region with many secondary arms. Surface energy shows that thermoelectric currents and fluid flow will persist. The flow will act to homogenise the liquid destabilising the equilibrium of the secondary arms, causing some regions to re-melt and others to solidify. This will continue until the velocity becomes zero, which if it is assumed occurs when the region becomes devoid of thermoelectric currents then the surface temperature must become constant. For a homogeneous solute concentration and neglecting surface energy anisotropy, this occurs when the local curvature becomes constant. Thus over an extended period of time, it is anticipated that this region will slowly minimise its surface area; this is highlighted in figure 7, where the absence of secondary branches within the microstructure is evident. Therefore, initially secondary branching may be encouraged and later suppressed.

Conclusion

The focus of this paper is to look at the complex nature of the interaction of thermoelectric currents and a magnetic field in undercooled liquid metal droplets in the absence of gravity.

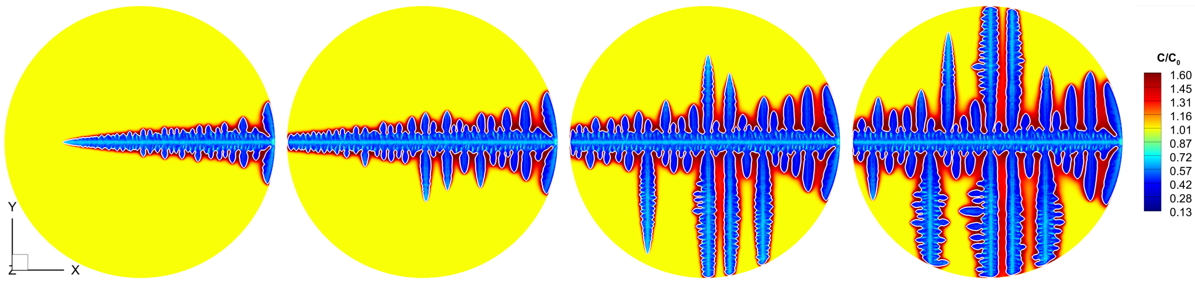

Figure 6: Solute field of droplet solidification with no external magnetic field.

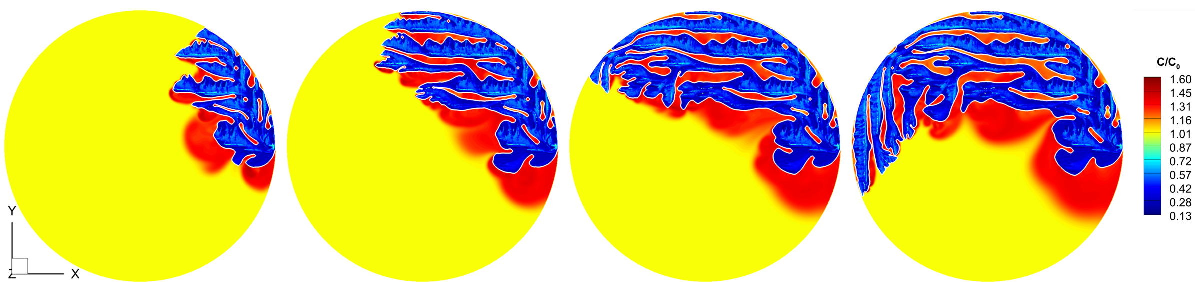

Figure 7: Solute field of droplet solidification with a 10T external transverse magnetic field.

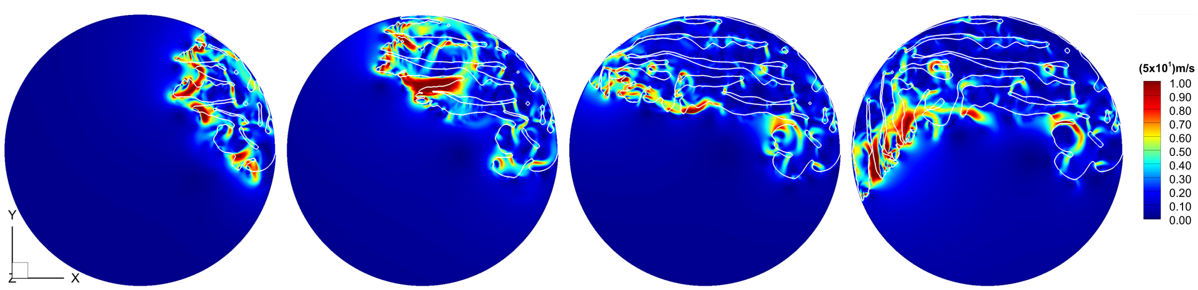

Figure 8: Relative $|\mathbf{u}|$ in an external magnetic field.

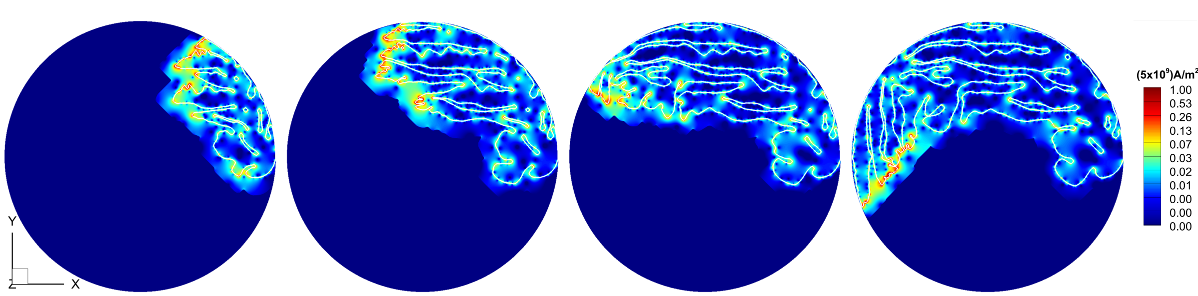

Figure 9: Relative $|\mathbf{J}|$ in an external magnetic field.

The 3-dimensional model highlights a variety of fluid microcirculations that all contribute to altering the convective transport and the evolution of dendritic growth. Perturbations from the flow of the thermal and mass boundary layer at the interface initiate secondary growth, altering the formation of thermoelectric currents, the Lorentz force and the velocity. Under a high magnetic field this intimate coupling results in a significant change to the dendritic structure and the numerical results indicate that an unexpectedly strong convection can develop within the inter-dendritic region. Using a quasi 3-dimensional approximation solidification of a droplet under a high magnetic field is also considered. The additional geometric constraints of the droplet surface give rise to a mesoscopic rotational flow, causing the dendrite to preferentially grow around the surface of the droplet. Downstream of this flow the thermal and mass boundary layers are extended as hot solute is ejected, stunting growth. As the solidification front propagates the microstructure continues to evolve through inter-dendritic flow and a hypothetical mechanism of the effect of this flow has been proposed.

References

[1] J. A. Shercliff, "Thermoelectric magnetohydrodynamics", *Journal of Fluid Mechanics*, 1978, 91 part 2, 231-251.

[2] V. R. Voller, "An enthalpy method for modelling dendritic growth in a binary alloy", *International Journal of Heat and Mass Transfer*, 2008, 51, 823-834.

[3] A. Kao, G. Djambazov, K. A. Pericleous and V. Voller, "Thermoelectric MHD in Dendritic Solidification", *Magnetohydrodynamics*, 45 No.3, 305-315, 2009.

[4] A. Kao, K. A. Pericleous, M. K. Patel and V. Voller, "Effects of magnetic fields on crystal growth", *International Journal of Cast Metal Research*, 22 No 1-4, 147-150, 2009.

[5] A. Kao "Thermoelectric magnetohydrodynamics in dendritic solidification", (Ph.D. thesis, University of Greenwich, 2010)

[6] A.Kao and K. Pericleous "The Effect of Secondary Arm Growth on Thermoelectric Magnetohydrodynamics", (Paper presented at the 8th Internatioal PAMIR Conference on Fundamental and Applied MHD, Borgo, Corsica, France, 5-9 September, 2011)

[7] A.Kao and K. Pericleous, "A numerical model coupling thermoelectricity, magnetohydrodynamics and dendritic growth", *Journal of Algorithms and Computational Technology*, 2012, Vol 6 (1), 50-77

[8] T.Tsukada, H.Fukuyama and H.Kobatake, "Determination of Thermal Conductivity and Emissivity of Electromagnetically Levitated High-Temperature Droplet based on the Periodic Laser-Heating Method: Theory.", *International Journal of Heat and Mass Transfer*, 2007, 50, 3054-3061