ABSTRACT

During solidification of non-eutectic alloys, non-isothermal phase change causes dendritic growth of solid front with liquid phase entrapped within the dendritic network producing the mushy region. Solidification causes rejection of solute at the solid-liquid interface and within the mushy zone, causing a sharp concentration gradient to build up across the mushy region. At the same time, a temperature gradient is present as a result of externally imposed boundary conditions as well as due to evolution of latent heat, giving rise to the so-called “double-diffusive” or thermo-solutal convection. Depending on the relative density of the solute being rejected in the liquid phase during solidification process, thermal and solutal buoyancy can either aid or oppose each other. Rejection of a heavier solute leads to aiding thermo-solutal convection situation whereas the rejection of lighter solute causes the thermal and solutal buoyancy to oppose each other. If the thermal and solutal buoyancies oppose each other, flow instability arises adjacent to the mush-bulk liquid interface regions. Thus, there may be a wide variety of convection situations present in the solidifying domain for different combinations of solution concentrations and externally imposed boundary conditions.

The situation becomes even more complex if the solid phase movement along with the bulk flow is involved in the process, leading to multiphase convection. Detachment of solid phase from the solid/liquid interface can be caused by remelting (solutal and/or thermal) and shearing action of a convecting liquid adjacent to the interface. Depending on the drag of the bulk flow and the density of the solid phase relative to that of the bulk liquid, these detached particles can either float or sediment.

The redistribution of the rejected solute by means of diffusion (at a local scale) and thermo-solutal convection (at system level length scales) causes heterogeneous orientation of mixture constituents over the solidifying domain popularly known as macro-segregation. From the point of view of manufacturing, severe form of macro-segregation or heterogeneous species distribution is an undesirable phenomenon and hence, a thorough understanding of the species redistribution by means of diffusion and convection during solidification process is very important.

Most of the earlier studies on double diffusive convection during solidification involved fixed dendrites. However, the advection of solid particles during the solidification process can generate major instability in the flow pattern while modifying the solid front growth, and hence the macro-segregation pattern considerably.

With this viewpoint in mind, the overall objective of the present work is to address these wide-varieties of single phase and multi phase flow situations and their effect on solid front growth and macro-segregation during directional solidification of non-eutectic binary alloys, numerically as well as experimentally. Different configurations of directional solidification processes involving double diffusive convection have been studied for two different kinds of non-eutectic solutions. While solidification of hypoeutectic solutions leads to aiding type double diffusive convection,
the solidification of hyper-eutectic solutions is characterized by opposing type double
diffusive convection. Solidification of hypo-eutectic solution generally involves single
phase flow, while most of the hyper-eutectic solidification involves movement of solid
phase (i.e. multiphase flow).

As far as the modeling part is concerned, transport phenomena during
solidification with multiphase convection are not common in existing literature. This
work is a first attempt to develop a solidification model with multiphase flow based
entirely on macroscopic parameters. As a first step, a generalized macroscopic
framework has been developed for mathematical modeling of multiphase flow during
solidification of binary alloy systems. The complete set of equivalent single-domain
governing equations (mass, momentum, energy and species conservation) are coupled
with the phase (solid and liquid) velocities. A generalized algorithm has been developed
to determine solid detachment and solid advection phenomena, based on two critical
parameters, namely: critical solid fraction and critical velocity. While the first of these
two parameters (critical solid fraction) represents the strength of the dendritic bond, the
second (critical velocity) stands for the intensity of flow to create drag force and solutal
remelting at the dendrite roots. A new approach for evaluating liquid/solid fraction by
using fixed grid enthalpy updating scheme, that accounts for multiphase flow and, at the
same time, handles equilibrium and non equilibrium solidification mechanisms, has been
proposed. The newly developed model has been validated with existing literatures as well
as with experimental observations performed in the present work.

The experimental results were obtained by using PIV as well as laser
scattering techniques. Side cooled as well as top cooled configurations are studied. Single
phase convection is observed for the case of hypo-eutectic solution, whereas hyper-
eutectic solutions involve convection with movement of solid phase. For the case of
bottom cooled hyper-eutectic solution, finger-like convection leading to freckle formation
is observed. For all the hyper-eutectic cases, solid phase movement is found to alter the
convection pattern and final macrosegregation significantly. The numerical results are
compared with experimental observations both qualitatively as well as quantitatively.