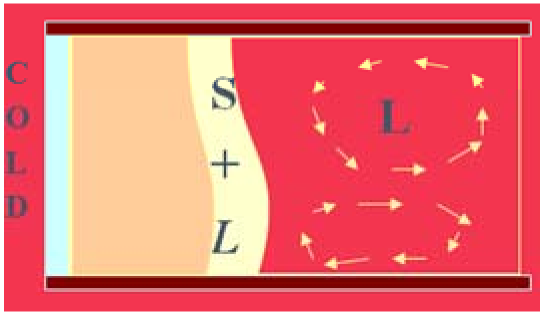
Solidification – physical phenomena

- ✓ Two-phase solid-liquid (mushy) zone
- ✓ Transport phenomena (heat, mass, fluid flow), shrinkage

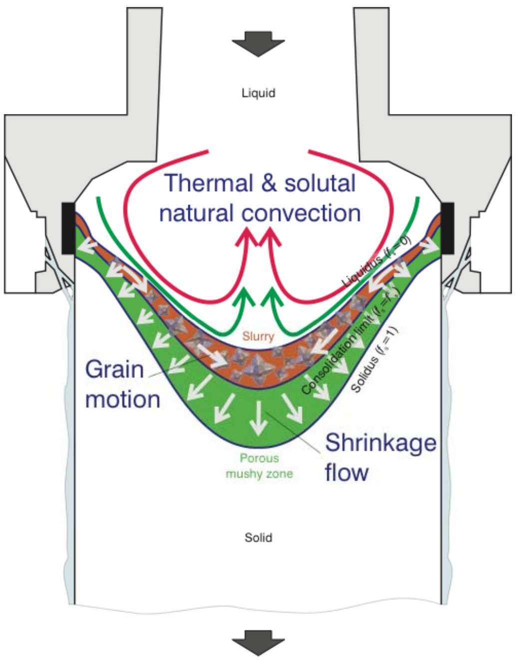


Convection

Causes of melt flow during casting

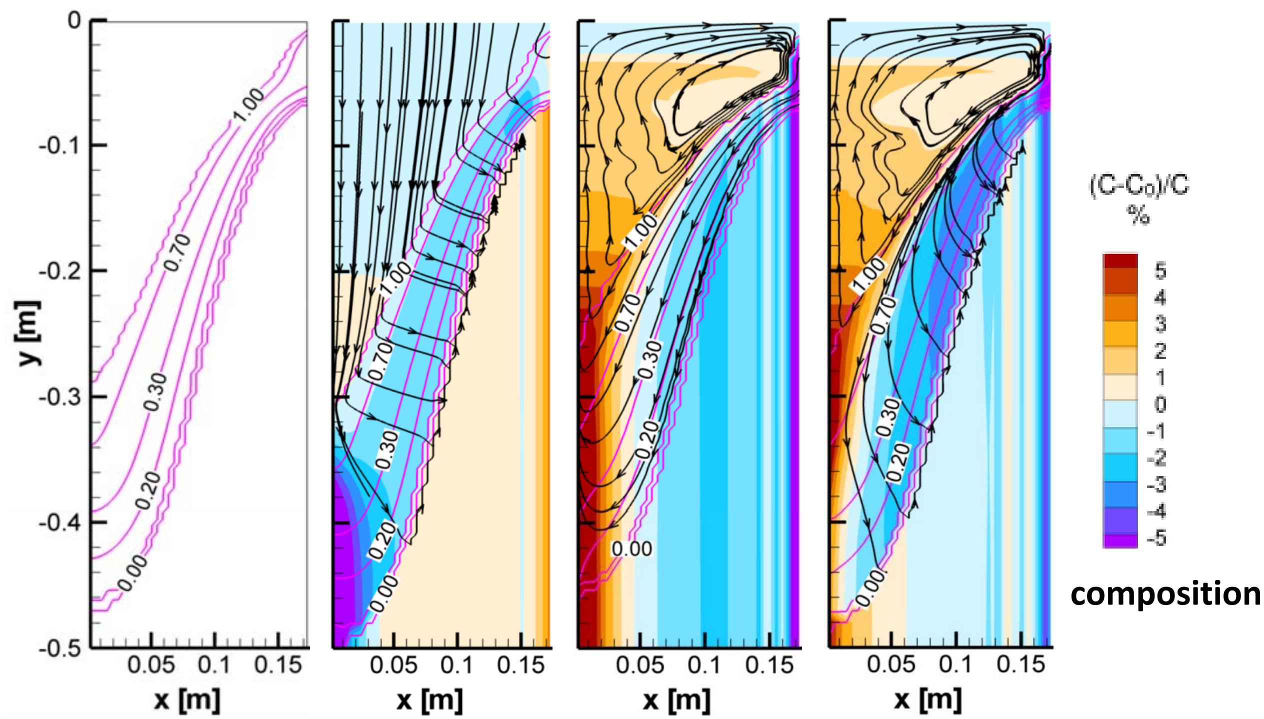
- Shrinkage
- Natural convection
- Forced convection
- Surface tension (Marangoni convection)

Shrinkage driven flow



Direct chill (DC) casting process

Various simulation case studies



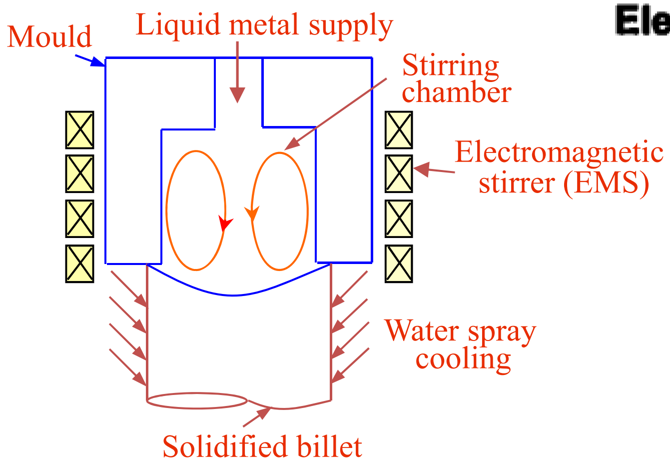
No flow

only shrinkage

only natural convection

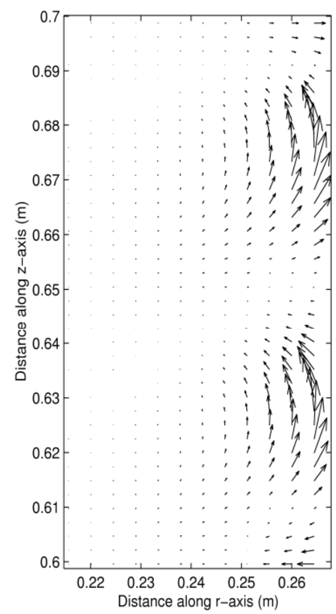
natural convection + shrinkage

Forced convection

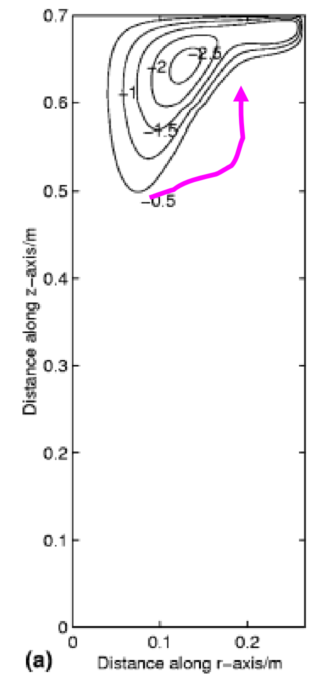


Continuous Casting with linear Electromagnetic stirring

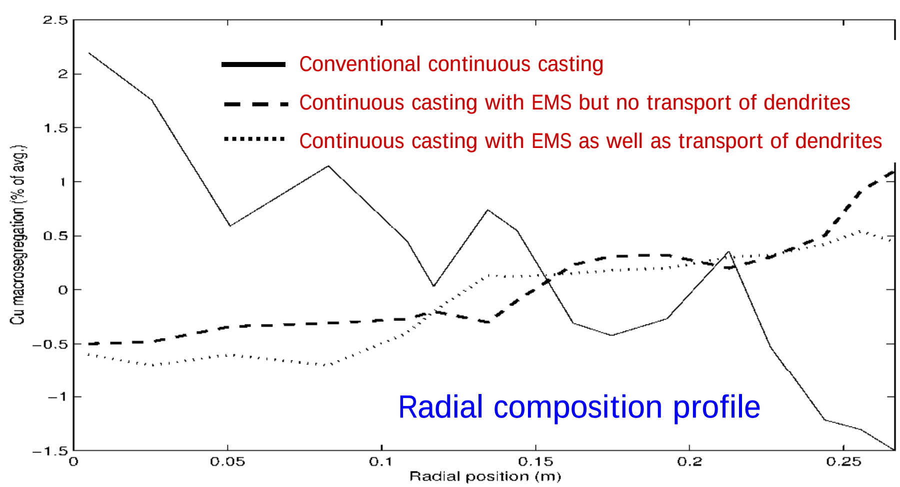
Electromotive Force or Lorentz Force $\mathbf{F_{em} = J \times B}$



Loretz force field



Flow pattern by streamlines



$$U_{\mathrm{ref}} \sim \left\{ \left[\left(g(\beta_T \Delta T - \beta_S \Delta C) + \frac{(J \times B)_z}{\rho_{ref}} \right) Z \right] \right\}^{1/2}$$

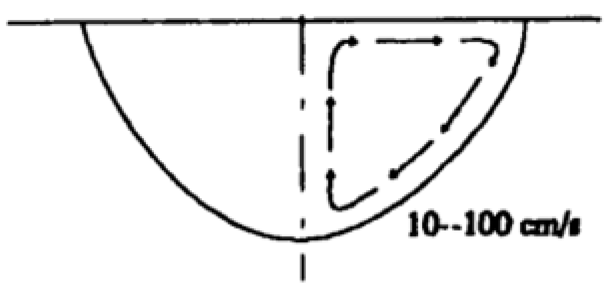
Dependence of flow velocity on Lorentz force

Marangoni convection

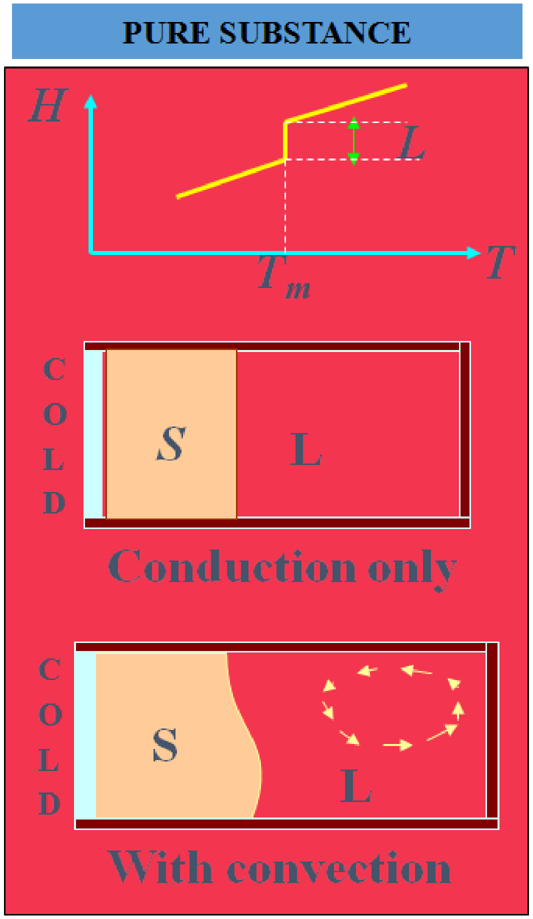
Surface Gradient Force or Marangoni Convection $\mathbf{F}_\gamma = -\dfrac{d\gamma}{dT}\nabla T$

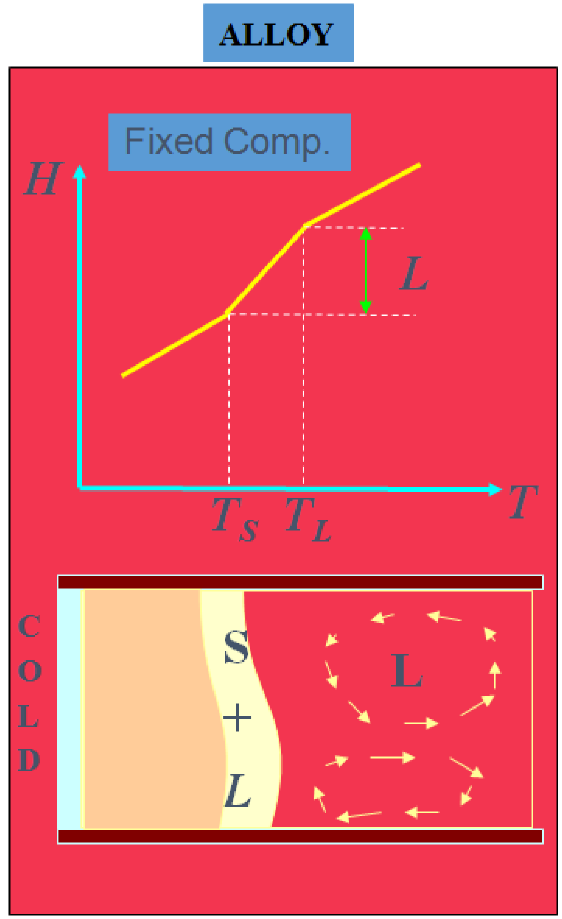
where γ is the surface tension of the molten metal, T is the temperature, and ∇T is the temperature gradient at the weld pool surface

Thus, whenever a temperature gradient exists in a liquid, so too does a gradient in surface tension. This gradient exerts a force



Solidification: Natural convection in Pure substance vs Alloy





$$\rho = \rho_o\left[1 - \beta_C^o(C - C_o) - \beta_T^o(T - T_o)\right]$$

$$\nabla T = m_l \nabla C \qquad N = \frac{|\beta_C|}{|m_L \beta_T|}$$

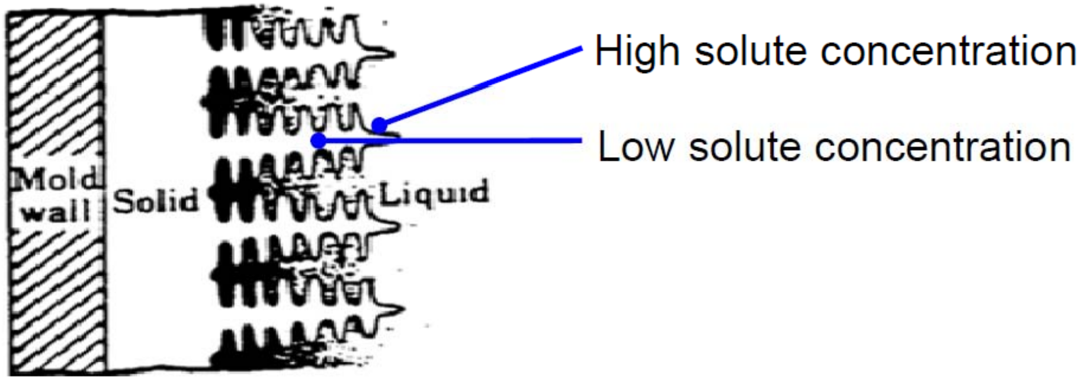
Specifics of alloy solidification

- Unlike pure substances, alloys do not have a sharp interface between the solid and the liquid phases
  - Solidification occurs over a range of temperature
  - Mushy zone exists between phases
  - Co-existence of thermal and solutal buoyancy

- Composition variations – segregations
  - Solute is re-distributed as solidification occurs
  - Solute transport has to be solved along with momentum and energy

Segregation

Solidifying material “rejects solute atoms into liquid



Effects of segregation

- **Composition changes throughout casting**
- **Density changes result in circulation and convection**
- **Heat treat/homogenization times increase**

Defects in casting: macro/ mesosegregation

- Redistribution of solute at the macro/ meso scale during solidification
- Redistribution caused by
  - diffusive transport
  - convective transport
    - natural convection
    - forced convection
    - Shrinkage driven flow
    - Marangoni convection (surface tension) driven flow

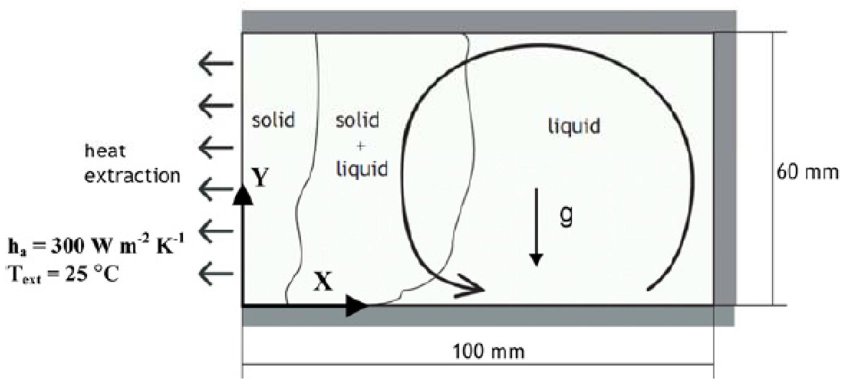
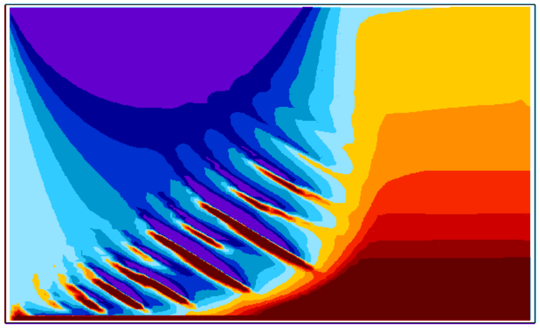


Table 1
Thermophysical data and parameters used in the 2D computation.

Parameter	Sn-5 wt% Pb
Phase diagram	
Initial mass fraction, wt% Pb	5.0
Melting temperature, °C	232.0
Eutectic temperature, °C	183.0
Liquidus slope, °C $wt\%^{-1}$	−1.286
Eutectic mass fraction, wt%Pb	38.1
Partition coefficient, –	0.0656
Thermophysical data	
Specific heat, J kg^{-1} K^{-1}	260.0
Thermal conductivity, W m^{-1} K^{-1}	55.0
Latent heat of fusion, J kg^{-1}	61,000
Reference mass density, kg m^{-3}	7000.0
Reference temperature for mass density, °C	226.0
Thermal expansion coefficient, $°C^{-1}$	6.0×10^{-5}
Solutal expansion coefficient, wt $\%^{-1}$	-5.3×10^{-3}
Dynamic viscosity, kg m^{-1} s^{-1}	10^{-3}
Computational parameters	
Initial temperature, °C	226.0
Heat transfer coefficient, W m^{-2} K^{-1}	300.0
External temperature, °C	25.0
Dimension of the cavity ($X \times Y$), m	0.1×0.06
Number of nodes, $X \times Y$ directions	150×150
Value of the representative size in the dendritic structure (in section 3.2), µm	100.0

How betas control macro/ mesosegregation by governing flow directions

C-C_0

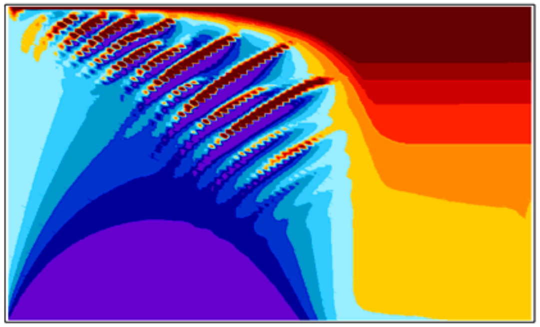


β_C (**- 5.3×10^{-3} wt %$^{-1}$**)

Sn-5%Pb alloy (Solute Pb, heavier)

β_T = 6.0×10^{-5} °C^{-1}
m_L = -1.286 °C wt %$^{-1}$
β_C = -5.3×10^{-3} wt %$^{-1}$

$$N = \frac{|\beta_C|}{|m_L \beta_T|} \approx 65$$



Opposite β_C (+ **5.3×10^{-3} wt %$^{-1}$**)

Pb-5%Sn alloy (Solute Sn, lighter)

The **Grashof number** (**Gr**) is a dimensionless number in fluid dynamics and heat transfer which approximates the ratio of the buoyancy to viscous force acting on a fluid. It frequently arises in the study of situations involving natural convection.

$$\mathrm{Gr} = \frac{\beta g \Delta T L^3}{\nu^2}$$

In forced convection the **Reynolds Number** governs the fluid flow. But, in natural convection the **Grashof Number** is the dimensionless parameter that governs the fluid flow.

In fluid mechanics, the **Rayleigh number** (**Ra**) for a fluid is a dimensionless number associated with buoyancy driven flow (also known as free convection or natural convection). When the Rayleigh number is below the critical value for that fluid, heat transfer is primarily in the form of conduction; when it exceeds the critical value, heat transfer is primarily in the form of convection.

$$\mathrm{Ra}_x = \frac{g\beta}{\nu\alpha}(T_s - T_\infty)x^3 = \mathrm{Gr}_x \mathrm{Pr}$$