Phase change phenomena for a high Prandtl number fluid in a square cavity: Effect of angle of inclination

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Abstract : Solidification of a high Prandtl number fluid in a square closed cavity, in presence of for angle of inclination of 0 and 45 degree has been investigated. Effect of angle of inclination on solidification front shape and flow in the mushy zone is studied, during the growth process. Flow strength in the fluid to reduce with time, with lower strength in case of cavity inclined at angle of 45 degree. Flow in the solid zone is diffusion dominant and is of same size and structure for both the cavity orientation.

Keywords: Phase change, angle of inclination, streamline, fluid flow.

I. Introduction

Control of solidification process is crucial in different industrial processes like welding, casting, growth of semiconductor single crystal etc. The fluid flow and temperature field in the melt flow as well as the mushy zone and movement of melt liquid interface is of vital importance and dictates the quality of the final product developed. Growth of good quality single crystal requires precise control of shape of liquid melt interface [1].

In recent times because of development in numerical techniques, better understanding of physical process and computational power has lead to more emphasis on numerical investigation of phase change problems. Comparison of fixed grid enthalpy method and moving grid technique can be found in work of R Vishwanath and Y Jaluria [2]. Details of enthalpy based macro and micro scale models for solidification can be given by Pradip Datta [3].

The present numerical investigation aims to study the flow field, temperature field and movement of liquid melt interface during solidification in two dimensional cavity for a high Prandtl number fluid for angle of orientation of 0 and 45 degree, using enthalpy formulation. Fluid under consideration is assumed to solidify over range of temperature, as is the case for most alloys.

II. Mathematical Model and Geometry under Consideration

The present numerical investigation makes use of enthalpy based formulation on fixed grid for simulating the phase change process and track the growing liquid melt interface. Conservation of mass, momentum and energy equation for incompressible flow in unsteady state have been solved. Pressure velocity coupling has been achieved using SIMPLE algorithm by S Patankar[4]. Rhei Chow interpolation has been employed for correction for mass flux at the control surface, thus eliminating chance of occurrence of checkerboard pressure field

Details of the formulation like update of latent heat, suppressing of flow in the solid zone using artificial large source term etc can be found in work by Prakash and Voller [6]. Flow in mushy zone has been simulated using equation similar to Darcy's equation for porous media. Enthalpy after every iteration is updated using formulation suggested by S Chakrabarty and Pradip Dutta [5].Geometry under consideration is shown in Figure:1. The top and bottom surface are insulated where as the left and right solid surface are maintained at constant temperature. Values of different parameters used for numerical simulation are similar to those used by Praksah and Voller [6] and are listed below in Table. 2.1.

Table:2.1 Input parameters used for simulation

Initial temperature	0.5
Hot wall temperature (T_H)	0.5
Cold wall temperature(T_C)	-0.5
Reference temperature	0.5
Density	1
Viscosity	1
Thermal conductivity	0.001
Specific heat	1
Coefficient of thermal expansion	0.01
Gravity along Y direction	1000 cos(α)
Latent heat	5
Half mushy rage (ε)	0.1

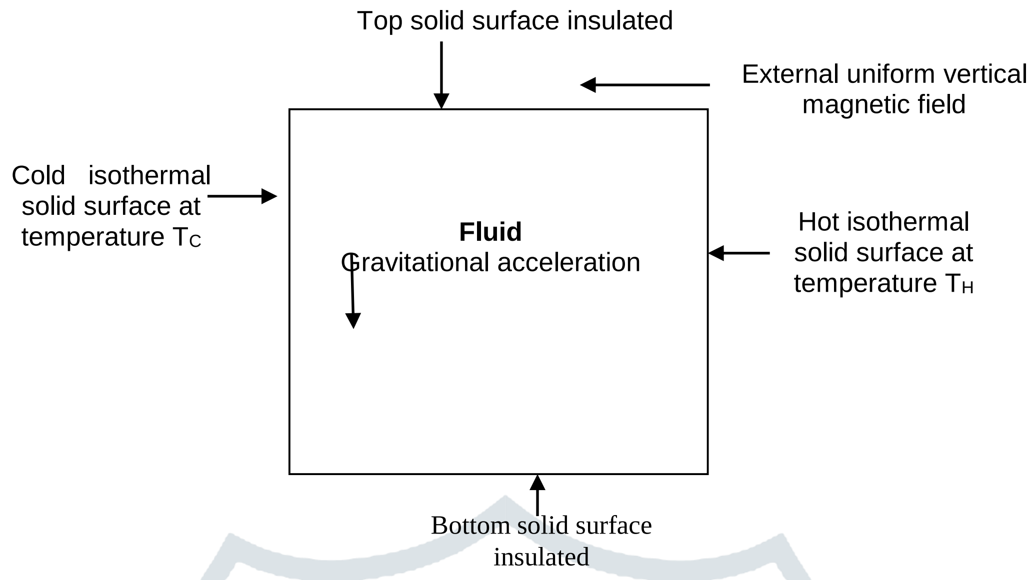

Figure: 2.1 Melt growth geometry under consideration.

III. RESULTS AND DISCUSSION

Development of flow and temperature field inside cavity for different time instants is shown in Fig. 3.1. Fluid inside the cavity in contact with the left side cold wall loses heat and experiences a drop in temperature. At time level t=100, some part of the fluid has transferred into solid by transferring heat of solidification to the cold left isothermal surface. The liquidus line T=0.1 is almost vertical in the initial stage of growth process. This is owing to the fact that diffusion is the dominant mode of heat transfer during initial stage.

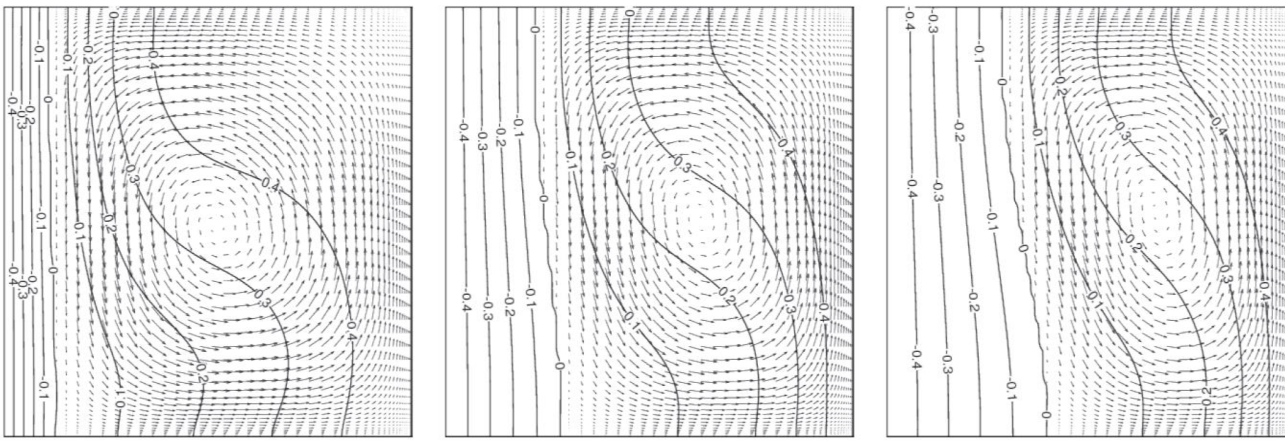

Figure: 3.1 Isotherm and vector plot for 0 degree inclination at t=100,t=500 and t=1500.

The liquidus line moves forward towards the right side of the cavity with passage of time, with solid on the left side and liquid on the right. Vertical parallel isotherms in the solid zone show diffusion dominant heat transfer to the cold wall on the left side.

Fluid near the right hot isothermal surface gets heated and under influence of buoyant force rises towards the top insulated surface where it turns towards the left wall. Near the liquidus line (T=0.1) and also in the mushy zone, the fluid gives up heat energy, becomes heavy and moves towards the bottom surface and subsequently moves back towards the hot surface thus completing the counter clockwise rotation cell.

Size of the counter clockwise rotating cell near the right side hot wall reduces and circulation strength too gets weaker with passage of time as seen for the value of maximum stream function in Table 3.1.

Table 3.1. Values of maximum stream function inside the cavity.

	t=100	t=500	t=1500
0 degree inclination	0.003610	0.003039	0.002651
45 degree inclination	0.002908	0.001464	0.001391

Tilting the cavity to an angle of 45 degree in anticlockwise direction results in lower strength of buoyancy driven natural convection inside the liquid zone as seen on Fig. 3.2. Here too with passage of time, the liquidus line moves towards the right side. However for time t=1500 the isotherms are almost vertical in the liquid zone showing significant reduction in the circulation strength. The same is also seen from the values of stream function in Table. 3.1.

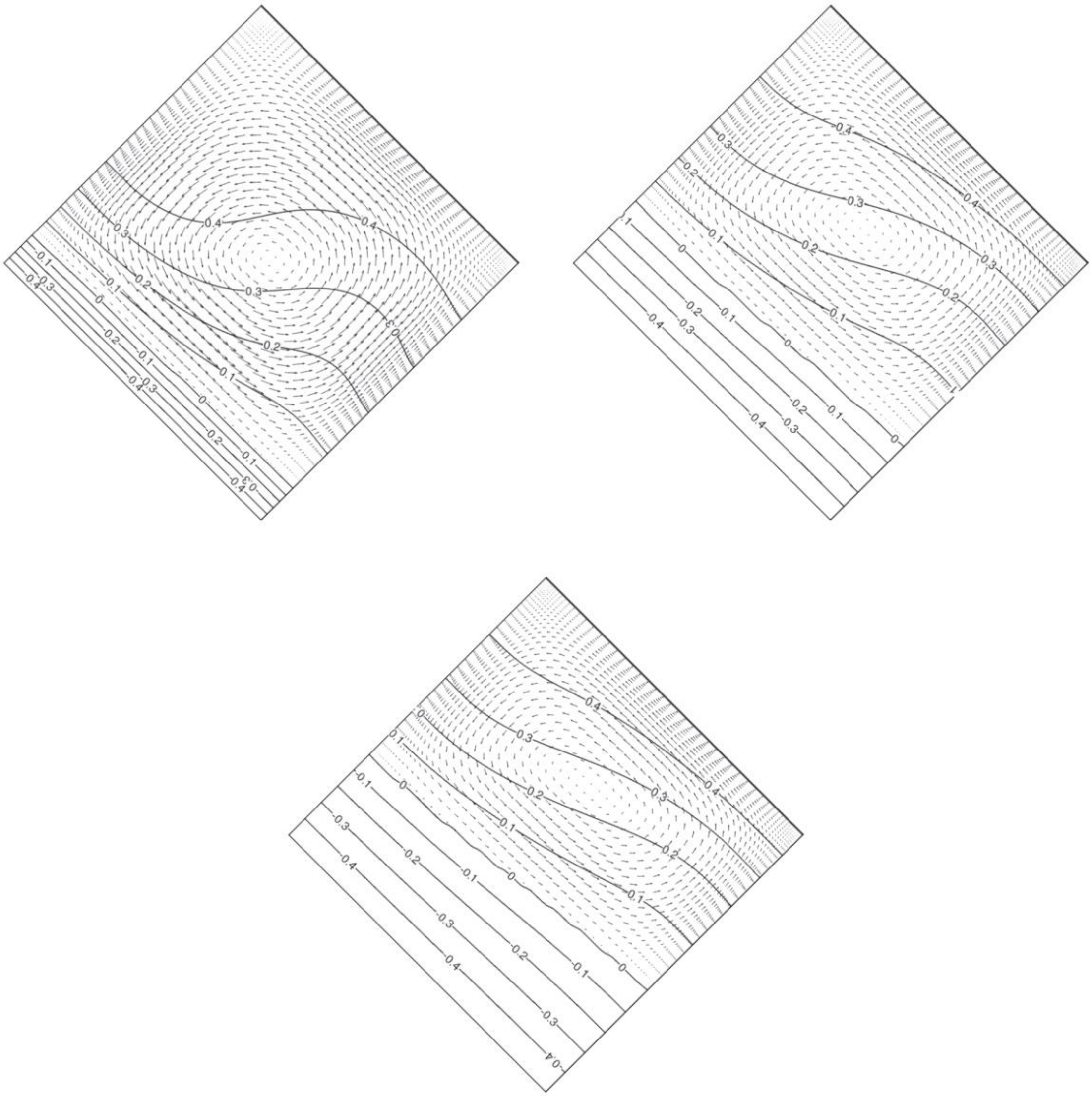

Figure: 3.2 Isotherm and vector plot for 45 degree inclination at t=100,t=500 and t=1500.

Evolution of isotherm and streamline contours for the cavity with angle of inclination of zero (red color) and angle of inclination of 45 degree (black color) is shown on the same plot in Fig. 3.3. For a given time instant, there is hardly any difference in isotherms inside the solid zone towards the cold left wall. However, inside the fluid zone, higher circulation strength for zero degree inclination case results in the isotherms near the top adiabatic wall being pushed further towards the cold wall as compared to the case of cavity at angle of inclination of 45 degree. Size and location of the counter clockwise rotating cell is the same for both cavity inclination angles. However, strength of circulation is lower for cavity at angle of inclination of 45 degree which further reduces with passage of time as seen in Table. 3.1.

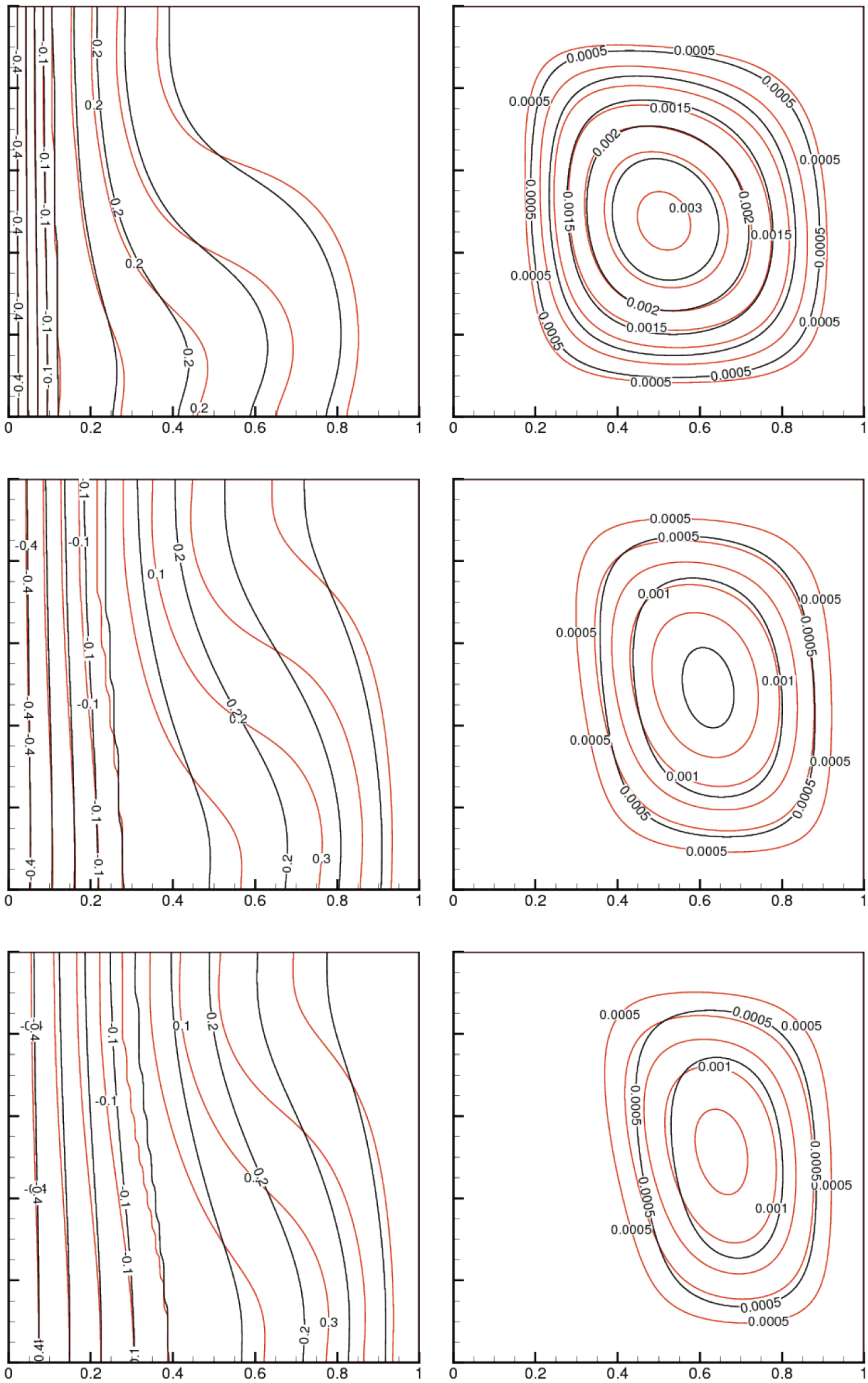

Figure: 3.3 Isotherm and streamline contours for 0 degree (red) and 45 degree (black) inclination at t=100,t=500 and t=1500.

IV. CONCLUSION

Phase change phenomena inside a square cavity for angle of inclination of 0 and 45 degree has been simulated. Flow strength is found to reduce with passage of time for both angles of inclination, with lower circulation strength in case of cavity inclined at angle of 45 degree. Temperature distribution in the solid zone is the same for both angle of orientation. Isotherms contours near the top adiabatic surface are pushed more towards the cold wall in case of cavity at angle of 0 degree.

V. REFERENCES

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