

# Contents

	page
Abstract	i
Acknowledgements	iii
Contents	v
List of Figures	vii
List of Tables	xi
Nomenclature	xiii
List of Abbreviations	xv
<b>Chapter 1: Introduction</b>	<b>1</b>
1.1 Solidification process	1
1.1.1 Solidification length scales	2
1.2 Macroscopic Solidification and Associated Mechanisms	3
1.2.1 Hydrodynamic Attributes	4
1.2.2 Thermal Attribute	6
1.2.3 Solutal Attribute	7
1.3 Important Outcomes from Macroscopic Solidification Modeling	8
1.3.1 Macro-shrinkage Defects	9
1.3.2 Macrosegregation	10
1.4 Objectives	10
1.5 Review of literature	11
1.5.1 Analytical macro-scale modeling of solidification shrinkage	11
1.5.2 Numerical macro-scale modeling of solidification shrinkage	13
1.5.3 Experimental investigation of directional solidification	17
1.6 Scope of the thesis	20
<b>Chapter 2: One-dimensional diffusion based solidification model with volumetric expansion and shrinkage effect: semi-analytical approach</b>	<b>23</b>
2.1 Introduction	23
2.2 Mathematical model	24
2.3 Validation and case studies	28
2.4 Summary	31
<b>Chapter 3: Cooling curve prediction for controlled unidirectional solidification under influence of shrinkage: semi-analytical approach</b>	<b>33</b>
3.1 Introduction	33
3.2 Mathematical Model	34
3.3 Validation and case studies	39
3.4 Summary	45
<b>Chapter 4: Shrinkage induced flow during directional solidification of pure substance in a bottom cooled cavity: A study on flow reversal phenomena</b>	<b>47</b>
4.1 Introduction	47
4.2 Mathematical Modeling	49
4.3 Numerical approach and volume fraction updating methodology	51
4.4 Experimental setup	54
4.4.1 Experimental procedure	55
4.5 Results and Discussion	56
4.5.1 Comparison 2-D shrinkage models with and without considering buoyancy effect	56
4.5.2 Experimental validation	59
4.5.3 Case studies	62
4.6 Summary	68
<b>Chapter 5: Effect of shrinkage induced flow on solutal instability and macro-segregation during directional solidification of binary alloys</b>	<b>69</b>
5.1 Introduction	69
5.2 Mathematical modeling	71
5.3 Numerical approach and physical domain	73

5.4	Results and discussion	74
5.4.1	Solidification of Al-4.1 wt.% Cu	74
5.4.2	Solidification of Al-30 wt.% Mg	76
5.4.3	Effect of grid size and time-step on numerical simulation	78
5.4.4	Effect of shrinkage induced flow on freckle formation	80
5.4.5	Effect of inlet opening size on macro-segregation during freckle formation	81
5.4.6	Effect of cold boundary temperature on macro-segregation	84
5.4.7	Scaling analysis	93
5.5	Summary	97
<b>Chapter 6: Shrinkage defects: Free surface deformation during solidification of Metal Alloys</b>		99
6.1	Introduction	99
6.2	Mathematical Modelling	99
6.3	Result and Discussion	102
6.3.1	Validation	102
6.3.2	Solidification of pure aluminium in a rectangular mould with riser	103
6.3.3	Solidification of pure aluminium in a rectangular mould cavity with open top	104
6.3.4	Solidification of pure Al-4.1 wt.% Cu alloy in a rectangular mould cavity with open top	107
6.4	Summary	108
<b>Chapter 7: Concluding remarks and scope for future work</b>		111
7.1	Conclusions	111
7.1.1	One-dimensional diffusion based solidification model with volumetric expansion and shrinkage effect: semi-analytical approach	111
7.1.2	Cooling curve prediction for controlled unidirectional solidification under influence of shrinkage: semi-analytical approach	111
7.1.3	Shrinkage induced flow during directional solidification of pure substance in a bottom cooled cavity: A study on flow reversal phenomena	112
7.1.4	Effect of shrinkage induced flow on solutal instability and macro-segregation during directional solidification of binary alloys	113
7.1.5	Shrinkage defects: Free surface deformation during solidification of Metal Alloys	114
7.2	Future scope	115
<b>References</b>		117
<b>Appendix A: Derivation of energy conservation equation as scalar variable temperature</b>		125
1	Energy equation for pure and alloy system without integrating free surface	125
2	Energy equation for pure and alloy system in presence of free surface	126
<b>Appendix B: SIMPLER algorithm for solution of continuity and momentum equations</b>		127
<b>Appendix C: Volume of Fluid Method</b>		129
<b>Appendix D: List of publications from the present investigation</b>		131
D1	Journal Articles	131
D2	Conferences	131