

**MATHEMATICAL MODELLING OF FLUID FLOW AND HEAT
TRANSFER UNDER ELECTROMAGNETIC FORCE IN THE
CONTINUOUS STEEL CASTING PROCESS**

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Thesis
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CONTINUOUS STEEL CASTING PROCESS**

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MATHEMATICAL MODELLING OF FLUID FLOW AND HEAT TRANSFER
UNDER ELECTROMAGNETIC FORCE IN THE CONTINUOUS STEEL
CASTING PROCESS

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ABSTRACT

The continuous steel casting process involves heat transfer, fluid flow and solidification, which effect the quality of steel. Hence, understanding these underlying phenomena is essential for optimizing the casting process and solving problems that have still not been fully understood. I have undertaken a mathematical study to model multi-phase flows including the flux flow and the molten steel flow in the continuous casting process. The work is mainly based on fluid dynamics and electromagnetic theory. The focus of the project is the construction of a mathematical model and the development of robust simulation technique. By incorporating Lorentz force into the model, the influence of an electromagnetic field on heat transfer and fluid flow can be simulated. The model is then illustrated with a numerical example which demonstrates that the thickness of the solidified steel shell critically depends on the magnitude of the Lorentz force. The Lorentz force prevents the molten steel from sticking to the mould wall. The numerical results show that the model is capable of analyzing the influence of an electromagnetic field on the flow pattern of fluid and the solidification profile of steel and could be used in solving technical problems in steel casting.

KEY WORDS : FINITE ELEMENT METHOD / ELECTROMAGNETIC
FLUID FLOW / HEAT TRANSFER / MENISCUS

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การจำลองแบบทางคณิตศาสตร์ของการไหลของของเหลวและการถ่ายเทความร้อนด้วยแรงจากสนามแม่เหล็กไฟฟ้าในกระบวนการหล่อเหล็กต่อเนื่อง (MATHEMATICAL MODELLING OF FLUID FLOW AND HEAT TRANSFER UNDER ELECTROMAGNETIC FORCE IN THE CONTINUOUS STEEL CASTING PROCESS)

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บทคัดย่อ

การหล่อเหล็กต่อเนื่องเกี่ยวกับปรากฏการณ์หลายอย่างเช่น การถ่ายเทความร้อน การไหลของของเหลว และการแข็งตัว ซึ่งปรากฏการณ์เหล่านี้มีผลกระทบต่อคุณภาพของเหล็ก ดังนั้นการเข้าใจปรากฏการณ์เหล่านี้จึงมีความจำเป็นสำหรับการพัฒนากระบวนการหล่อเหล็กต่อเนื่องให้มีประสิทธิภาพสูงขึ้น และแก้ปัญหาที่ยังคงเกิดขึ้น ดังนั้นการศึกษาในเชิงคณิตศาสตร์โดยการสร้างแบบจำลองเพื่ออธิบายปรากฏการณ์ต่าง ๆ ที่เกิดขึ้นในกระบวนการหล่อเหล็กโดยอาศัยความรู้ด้านพลศาสตร์ของไหลและทฤษฎีแม่เหล็กไฟฟ้าได้ถูกนำมาใช้ในวิทยานิพนธ์ฉบับนี้ โดยมีจุดประสงค์เพื่อพัฒนาแบบจำลองทางคณิตศาสตร์ และเทคนิคเชิงคำนวณสำหรับการวิเคราะห์ปัญหาของการไหลของน้ำเหล็ก การถ่ายเทความร้อนและการแข็งตัวของเหล็กเมื่อมีผลกระทบจากแรง Lorentz เข้ามาเกี่ยวข้อง ผลจากการศึกษาด้วยตัวอย่างการคำนวณแสดงให้เห็นว่า ขนาดแรงจากสนามแม่เหล็กไฟฟ้ามีผลต่อความหนาของชั้นเหล็กที่แข็งตัวที่บริเวณโดยรอบของเตาหล่อ อีกทั้งแรง Lorentz ช่วยป้องกันไม่ให้น้ำเหล็กติดที่ผนังของเตาหล่อ ดังนั้นผลเฉลยจากการคำนวณแสดงให้เห็นว่าแบบจำลองทางคณิตศาสตร์ที่ถูกนำเสนอนี้สามารถใช้ในการวิเคราะห์อิทธิพลของสนามแม่เหล็กไฟฟ้าต่อลักษณะของการไหลของของเหลวและการแข็งตัวของเหล็ก อีกทั้งยังสามารถใช้ในการแก้ปัญหาในกระบวนการหล่อเหล็กได้

CONTENTS

ACKNOWLEDGEMENTS	iii
ABSTRACT	iv
THAI ABSTRACT	v
LIST OF TABLES	viii
LIST OF FIGURES	ix
1 Introduction	1
1.1 An Overview of the Continuous Casting Process	1
1.2 Scope and Objectives	6
1.3 Outline of the Thesis	6
2 Literature Review	8
2.1 General Overview	8
2.2 Modelling of Fluid Flow and Heat Transfer	9
2.3 Modelling of Electromagnetic Field in Continuous Casting Process	10
2.4 Modelling of Fluid Flow and Heat Transfer at the Presence of an Electromagnetic Field	11
2.5 Modelling of Meniscus Phenomena	12
2.6 Concluding Remarks	13
3 Electromagnetic Field in Continuous Casting Process	14
3.1 General Overview	14
3.2 Boundary Value Problem for the Electromagnetic Field	14

CONTENTS (CONT.)

vii

3.3 Finite Element Method for the Electromagnetic Field	19
3.4 Numerical Studies	21
3.6 Concluding Remarks	22
4 Coupled Fluid Flow-Heat Transfer in Electromagnetic Casting	31
4.1 General Overview	31
4.2 Mathematical Model	32
4.3 Finite Element Formulation	37
4.4 Numerical Algorithm	49
4.5 Numerical Studies	52
5.6 Concluding Remarks	55
5 Dynamic Behavior at Meniscus Region	68
5.1 General Overview	68
5.2 Mathematical Model	68
5.3 Moving Finite Element Formulation	70
5.4 Numerical Studies	80
5.5 Concluding Remarks	82
6 Summary and Conclusions	85
6.1 Concluding Remarks	85
6.2 Further Works	86
REFERENCES	87
APPENDIX	94
BIOGRAPHY	114

LIST OF TABLES

3.1	Material parameters	23
3.2	Computation schemes	24
4.1	Parameters used in numerical simulation	53
4.2	Computation schemes	54
5.1	Parameters used in numerical simulation	84
5.2	Computation schemes	84

LIST OF FIGURES

1.1	Continuous casting steel plant.	2
1.2	The continuous casting process.	3
1.3	The layers in the mould during casting	4
1.4	The electromagnetic stirring.	5
3.1	The computation domain for the electromagnetic problem.	18
3.2	The finite element mesh for the electromagnetic problem.	23
3.3	The contour plot of the magnetic vector potential $\mathbf{A}$ (Wb/m) at frequency $f = 60$ Hz and source current density $\mathbf{J}_s = 1000000$ A/m ²	25
3.4	The vector plot of the magnetic flux density $\mathbf{B}$ (Tesla) at frequency $f = 60$ Hz and source current density $\mathbf{J}_s = 1000000$ A/m ²	26
3.5	The contour plot of induced current $\mathbf{J}_e$ (A/m ²) in the continuous casting mould at frequency $f = 60$ Hz and source current density $\mathbf{J}_s = 1000000$ A/m ²	27
3.6	The vector plot of electromagnetic force F_{em} (N/m ³) in the electromagnetic continuous caster at frequency $f = 60$ Hz and source current density $\mathbf{J}_s = 1000000$ A/m ²	28
3.7	The influence of source current density $\mathbf{J}_s$ (A/m ²) on the magnitude of electromagnetic force in the continuous casting process at frequency $f = 60$ Hz.	29
3.8	The influence of the frequency of magnetic field f (Hz) on the magnitude of electromagnetic force in the continuous casting process at source current density $\mathbf{J}_s = 1000000$ A/m ²	30
4.1	Generation of finite element mesh from master element.	45
4.2	The computation domain and coordinate system.	56
4.3	The finite element mesh for the coupled fluid flow-heat transfer problem.	57
4.4	Vector plot of velocity vectors $\mathbf{u}$ (m/s) and temperature contours T (°C) when the coil current is off.	58

LIST OF FIGURES (CONT.)

x

4.5	Velocity vectors $\mathbf{u}$ (m/s) and temperature contours $T(^{\circ}C)$ under 60 Hz magnetic field and 30000 A source current.	59
4.6	Temperature profile $T(^{\circ}C)$ in the liquid steel pool : (a) without EM force, (b) with EM force under 60 Hz magnetic field and 30000 A source current.	60
4.7	Thickness of solidified steel shell in (a) with no magnetic field, (b) under 60 Hz magnetic field and 30000 A source current.	61
4.8	Temperature distribution of steel strand $T(^{\circ}C)$ in conventional continuous caster.	62
4.9	Temperature distribution of steel strand $T(^{\circ}C)$ in EM caster under 60 Hz magnetic field and 30000 A source current.	62
4.10	Temperature profile at the end of mould : label $-*-$ for a model without EM force and $---$ for a model with EM force under 60 Hz magnetic field and 30000 A source current.	63
4.11	The velocity fields of molten steel in the process for three different source currents : (a) 10000 A, (b) 20000 A, and (c) 30000 A. . . .	64
4.12	Temperature distributions of steel in the process for three different source currents : (a) 10000 A, (b) 20000 A, and (c) 30000 A. . . .	65
4.13	Thickness of solidified steel shell for different source currents : (a) 10000 A, (b) 20000 A, and (c) 30000 A.	66
4.14	Temperature profile ($^{\circ}C$) at the end of mould for different source currents : label $-*-$ for a model without EM force, and $---$ for a model with EM force.	67
5.1	Computation domain.	71
5.2	Generating mesh for flux and steel.	81
5.3	Flow patterns of liquid flux (labelled by black color) and liquid steel (labelled by red color) in (a) conventional casting process and (b) EM casting process.	82
5.4	Flow patterns of liquid flux (labelled by black color) and liquid steel (labelled by red color) for different source currents (a) 10000 A (b) 20000 A and (c) 30000 A.	83

CHAPTER 1

INTRODUCTION

1.1 An Overview of the Continuous Casting Process

Steel making industry is a large-scale industry comprising many production processes ranging from upstream processes to downstream processes as shown in Figure 1.1 [1]. The continuous steel casting process is the process for casting semi-finished steel products such as billet, slab and bloom. The process involves many complex phenomena such as heat transfer, flow of molten steel and flux, formation of oscillation marks on the steel surface, etc. Over the last few decades, the continuous casting process has been increasingly used to produce billet, slab and bloom. Over 80 % of the Western world steel products were casted by the continuous casting process in 1993 [2]. This ratio is expected to increase continuously due to the superiority of the continuous casting over the ingot casting in the following aspects:

- reducing energy consumption;
- savings in manpower;
- reduction in production costs;
- improvement of steel quality.

Although there are many different designs of the continuous steel caster, the schematic diagram of the continuous caster is as shown in Figure 1.2 [3]. The basic principle of the continuous casting process is to pour liquid steel into a water-cooled mould continuously. Due to the intense cooling by water running through channels in the mould wall, the solidified steel shell forms around the edges of mould. The solidified steel shell with a liquid pool at the center is

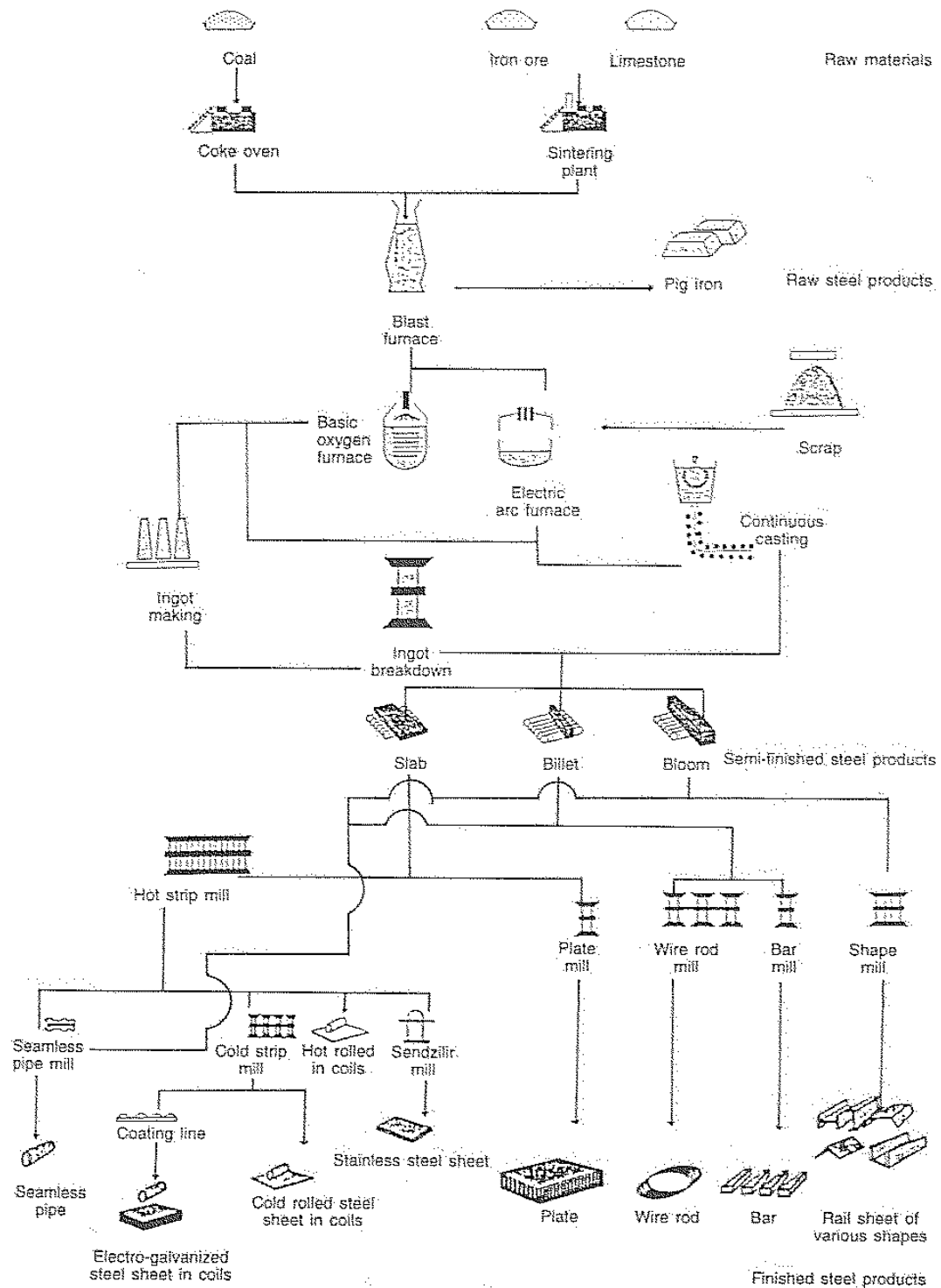


Figure 1.1: Continuous casting steel plant.

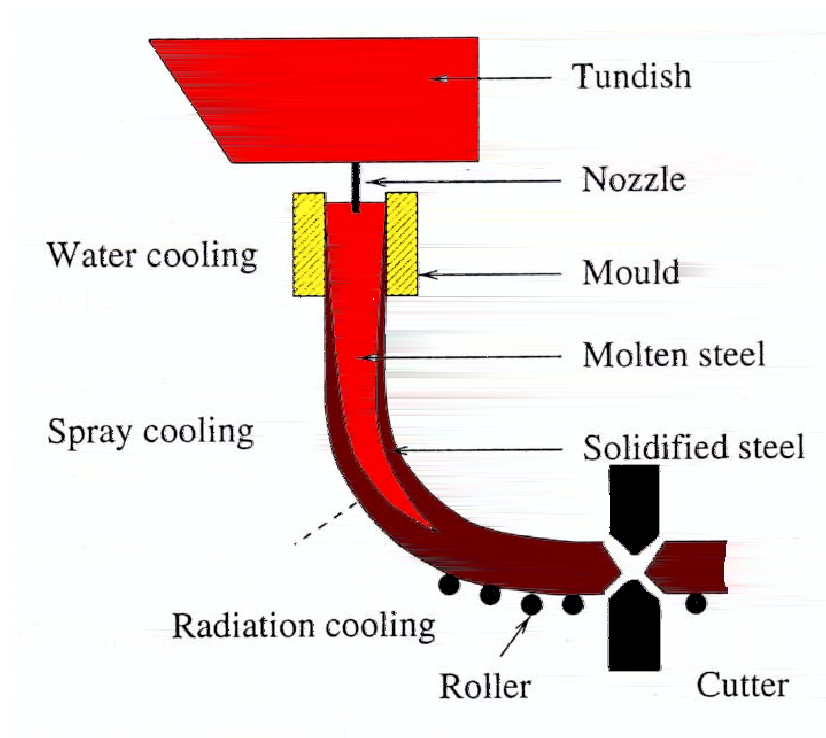


Figure 1.2: The continuous casting process.

withdrawn from the bottom of the mould at the casting speed under support of series of rolls which ensure that it is both rolled into shape and fully solidified at the same time. To facilitate the process and to avoid sticking of the solidified skin to the mould wall, the mould wall itself oscillates vertically. The lubrication oil or mould powder is added continuously at the top of the mould during the process to form a protective liquid flux layer. The liquid flux is drawn into the gap between the steel surface and the mould wall. The various layers formed in the mould during casting are shown in Figure 1.3 [4]. At the cutting point, the casting is cut to the required length.

Over the last few decades, many technologies have been developed and applied to the continuous casting process for improving the quality of the casting product and the production rate. The electromagnetic stirring technology is one of the most promising technologies. It is superior to the conventional continuous casting as it produces casting products with better quality including

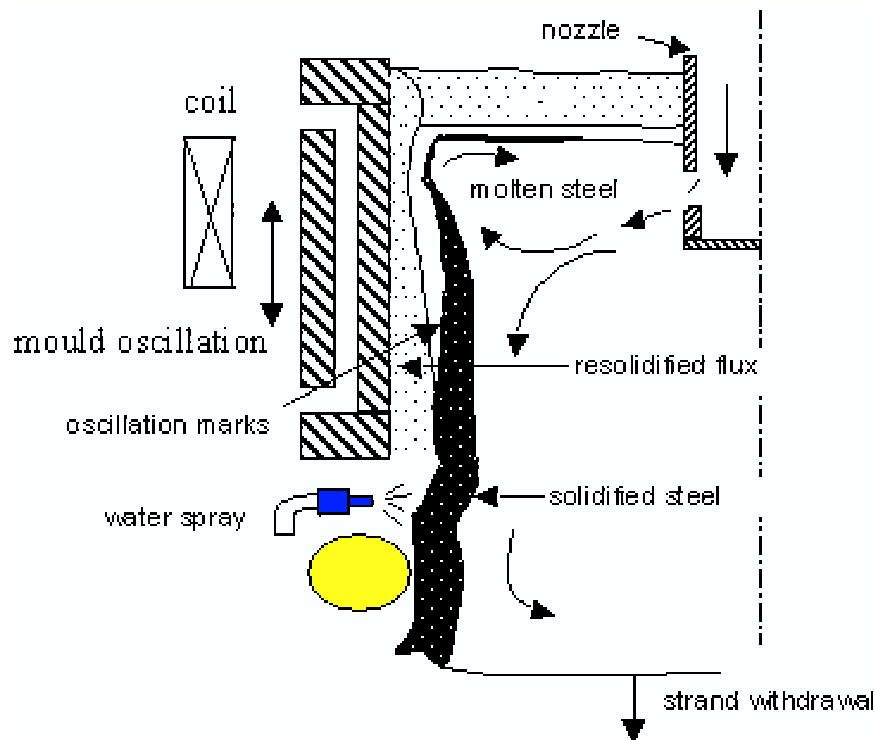


Figure 1.3: The layers in the mould during casting

- improved shearing ability by avoiding structures which cause cracks;
- better hot workability during extrusion forging;
- improved wire rod drawing performance with a low frequency of cup and cone breakages;
- higher and more consistent fatigue properties.

The schematic diagram of electromagnetic casting is shown in Figure 1.4. The basic concept of electromagnetic stirring is to generate induced currents in the steel by applying a moving electromagnetic field to the process. This force affects the flow of liquid steel, and consequently the solidification of the steel. Thus, with the electromagnetic stirring, it is possible to improve the steel surface quality, the internal segregation and structure of the steel [5, 6, 7, 8, 9]. Although this technology has been developed to reduce the occurring of operational problems and to improve the quality of steel products, various crucial problems still