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

JUTATIP ARCHAPITAK

A THESIS SUBMITTED IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR
THE DEGREE OF DOCTOR OF PHILOSOPHY (MATHEMATICS)
FACULTY OF GRADUATE STUDIES
MAHIDOL UNIVERSITY
2004

ISBN 974-04-5099-7

Thesis
entitled

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

....
Miss Jutatip Archapitak
Candidate

....
Assoc. Prof. Benchawan Wiwatanapataphee,
Ph.D.
Major-Advisor

....
Prof. I Ming Tang,
Ph.D.
Co-Advisor

....
Assoc. Prof. Yong Hong Wu,
Ph.D.
Co-Advisor

....
Assoc. Prof. Rassmidara Hoonsawat,
Ph.D.
Dean
Faculty of Graduate Studies

....
Assoc. Prof. Montip Tiensuwan,
Ph.D.
Chair
Doctor of Philosophy Programme
in Mathematics
Faculty of Science

Thesis
entitled

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

was submitted to the Faculty of Graduate Studies, Mahidol University
for the degree of Doctor of Philosophy (Mathematics)
on
July 23, 2004

....
Miss Jutatip Archapitak
Candidate

....
Assoc. Prof. Benchawan Wiwatanapataphee,
Ph.D.
Chair

....
Prof. I Ming Tang,
Ph.D.
Member

....
Lect. Winai Bodhisuwan,
Ph.D.
Member

....
Assoc. Prof. Yong Hong Wu,
Ph.D.
Member

....
Assoc. Prof. Rassmidara Hoonsawat,
Ph.D.
Dean
Faculty of Graduate Studies
Mahidol University

....
Prof. Prasert Sobhon,
Ph.D.
Dean
Faculty of Science
Mahidol University

ACKNOWLEDGEMENTS

I would like to thank Assoc. Prof. Dr. Benchawan Wiwatanapataphee, my advisor, for her guidance and encouragement. All advices have been of great value to me in the research and preparation of this thesis.

I wish to thank my co-advisor, Prof. Dr. I Ming Tang, for his kindness and his encouragement.

I would like to thank Assoc. Prof. Dr. Yong Hong Wu, my co-advisor, for his kindness, valuable advices, and encouragement during the period of my visit at Curtin University of Technology (Australia) in 2003.

I wish to thank Asst. Prof. Dr. Michael A. Allen for helping me to set up the Mahidol Thesis Latex style file.

I wish to thank the Department of Mathematics, Mahidol University and Department of Mathematics and Statistics, Curtin University of Technology for providing me with the necessary facilities.

I am very grateful to the Thailand Research Fund (TRF) and Development and Promotion of Science and Technology Talents Project (DPST) for the financial support during the period of my study.

Finally, I am greatful to my family and my friends for their encouragement.

Jutatip Archapitak

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

JUTATIP ARCHAPITAK 4237665 SCMA/D

Ph.D. (MATHEMATICS)

THESIS ADVISORS : BENCHAWAN WIWATANAPATAPHEE, Ph.D. (APPLIED MATHEMATICS), I MING TANG, Ph.D. (PHYSICS), YONG HONG WU, Ph.D. (APPLIED MATHEMATICS)

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

114 pp. ISBN 974-04-5099-7

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

จุฑาธิป อาชาพิทักษ์ 4237665 SCMA/D

ปร.ด. (คณิตศาสตร์)

คณะกรรมการควบคุมวิทยานิพนธ์ : เบญจวรรณ วิวัฒนปฐพี, Ph.D. (APPLIED MATHEMATICS), I Ming Tang, Ph.D. (PHYSICS), YONG HONG WU, Ph.D. (APPLIED MATHEMATICS)

บทคัดย่อ

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

114 หน้า ISBN 974-04-5099-7

CONTENTS

LIST OF TABLES

LIST OF FIGURES

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

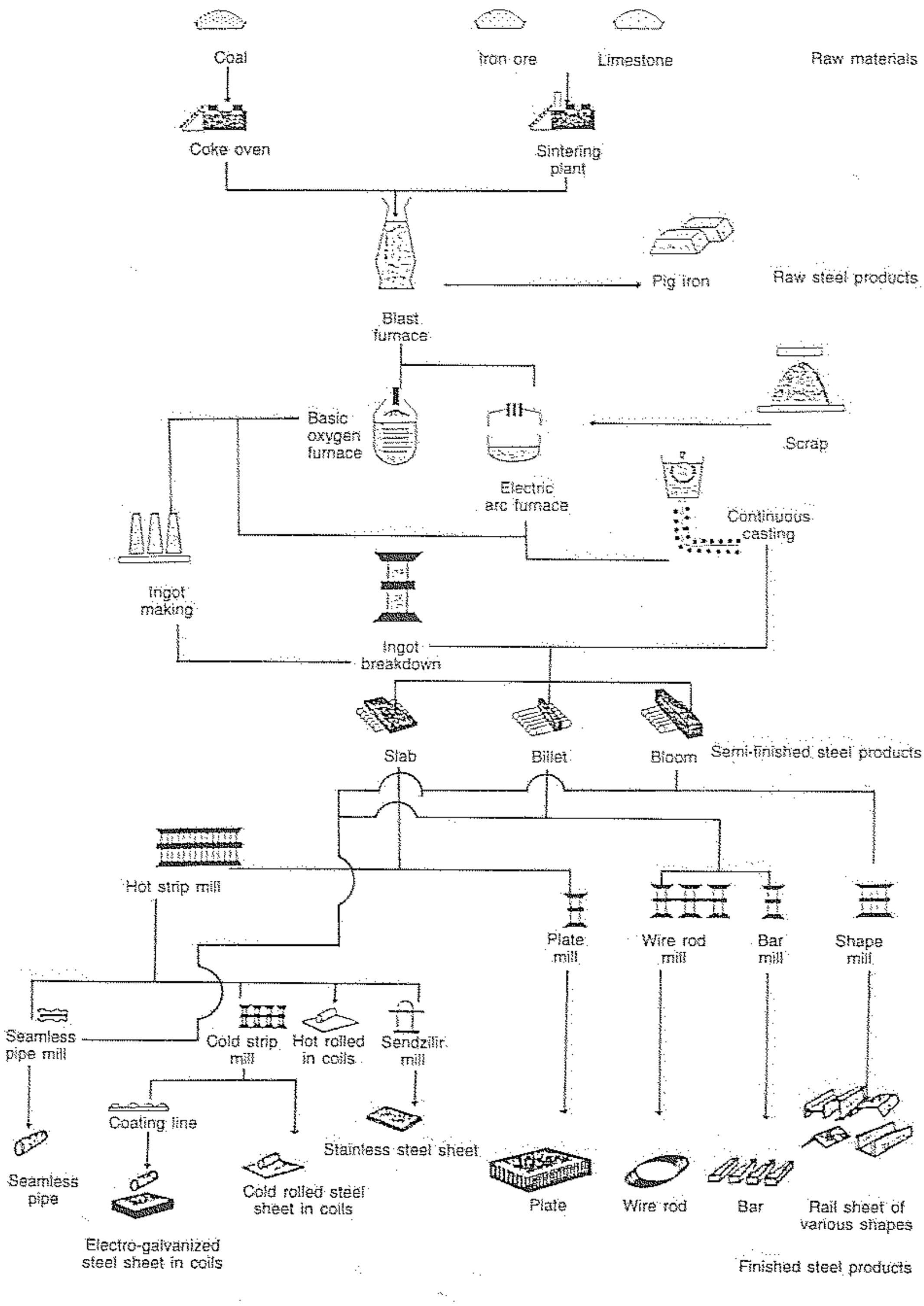

Figure 1.1: Continuous casting steel plant.

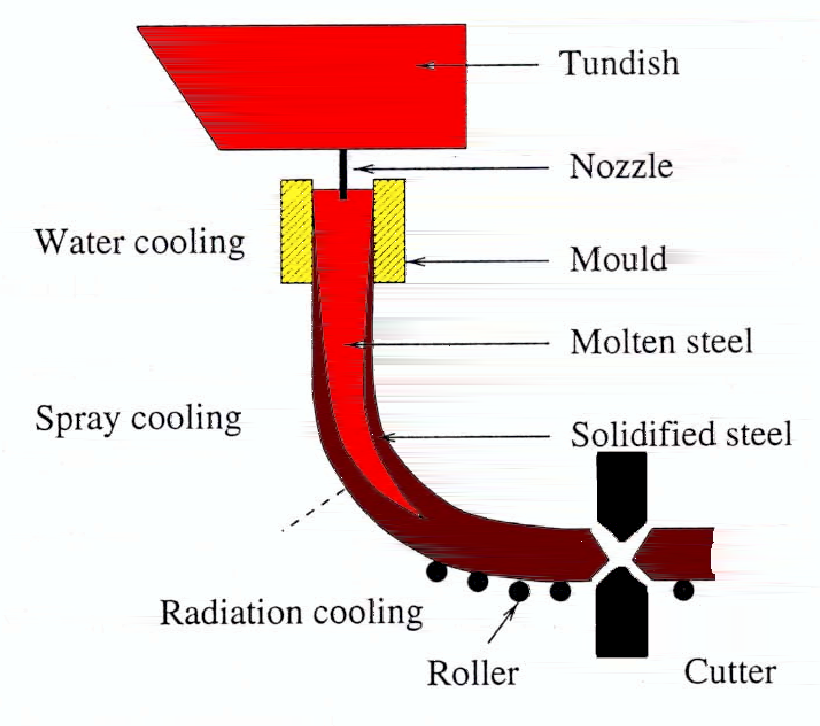

Figure 1.2: The continuous casting process.

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

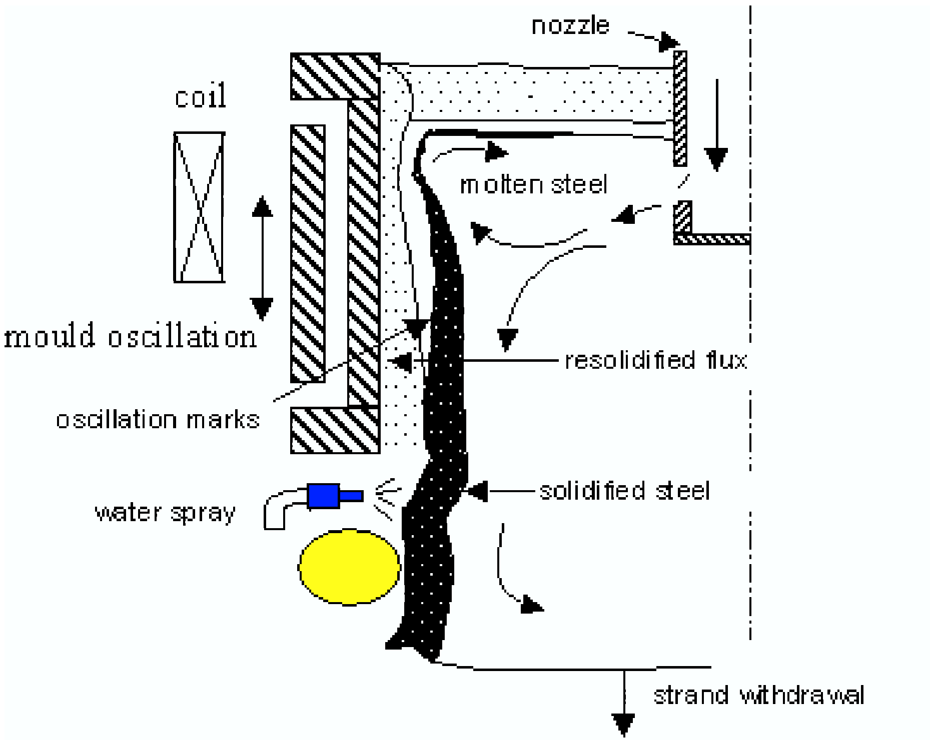

Figure 1.3: The layers in the mould during casting

- 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