CHAPTER 1: INTRODUCTION

Steel (whether it is low or high carbon steel, any alloy or a stainless steel alloy) is still the most reliable, appropriate and inexpensive building material for automobiles, trains, ocean liners, industrial vehicles, household appliances, industrial appliances and computer cases to name but a few. Even in a time where alternative materials (especially composites and plastics) are increasingly utilised, steel still seems to be irreplaceable owing to its availability, strength and price advantage above non-metallic materials that are equivalent in strength. Moreover, the recycling of steel is certainly an added advantage above composites and plastics from an environmental viewpoint.

Flat steel products in the form of rolled coils are mostly utilised for aforementioned applications. These coils are the result of a reduction process (hot or direct rolling) of billets, blooms or slabs[1] directly after casting (ingot casting[2] or continuous casting[3]). Since the quite recent commercial adoption of continuous casting (after World War II but only as a significant production process in the early 1960's) [1], it has practically replaced all ingot casting processes due to the increase in yield and reduced production costs. The energy savings (reduced production costs) are achieved primarily by elimination of the soaking pits and slabbing mill, and the possibility for direct rolling (no or much less reheating required).

[1] Definitions of billet, bloom and slab according to cross-section measurements: [8]
billet: square sections up to 150mm square or round sections up to 150mm diameter;
bloom: square or rectangular cross sections greater than 150mm square up to 800 x 400mm, also rounds with a diameter of more than 150mm diameter;
slab: anything larger than blooms; usually with an aspect ratio of more than 2.

[2] Ingot Casting: The cast of liquid steel into a stationary mould or ingot mould. Each mould consists of cast iron forming a thick walled container open at the top and set up before casting on large cast iron *bottom plates* or *stools*. After solidification, the ingot mould is removed with a *stripping crane* and the ingot is then charged into a soaking pit and slabbing mill, after which it is reheated and transported on rollers towards the final reduction process (rolling). [1][8]

[3] Continuous Casting: The cast of liquid steel into an open-ended mould, directly extracting the solidifying slab from the mould, eliminating the soaking pits and slabbing mill. Slabs are cut whilst moving at casting speed, directly transporting the cut slabs towards the hot reduction process resulting in a usable flat steel product.

The Submerged Entry Nozzle (SEN) plays a major part in the continuous casting process as indicated in other studies [2][3][4][5][6]: (Refer to Figure 1.1 [7] for diagrammatic presentation of the continuous casting process.)

The SEN introduces the molten steel emanating from the tundish into the mould, where the final particle removal process takes place in the continuous casting process. As the SEN introduces the flow to the mould, it has an effect on the flow pattern in the mould; consequently the SEN has an impact on the quality of the steel. The SEN, in particular the SEN geometry, has a primary influence on the flow pattern: the SEN controls the speed, direction and other characteristics[4] of the jet entering the mould.

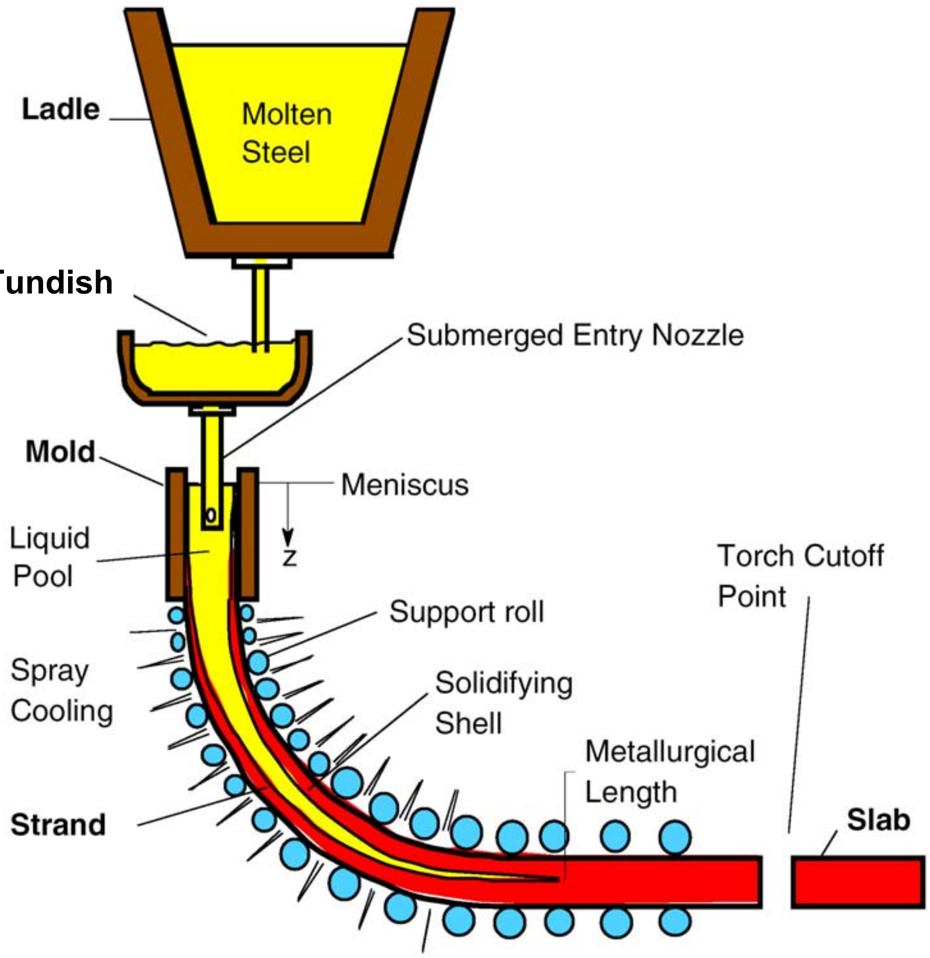

Figure 1.1: Continuous Casting process [7]

[4] Other characteristics of the jet emanating from the SEN may include turbulence effects, the occurrence of vortices, jet angle as it exits from the SEN, impingement point onto the narrow mould wall, impingement angle, etc.

The SEN geometry is however relatively inexpensive to change [5]. Thus; there is a feasible incentive to exactly understand and predict the flow of molten steel through the SEN and into the mould, in order to maximise the quality of the steel by altering the design of the SEN.

It is conceivable that by changing the SEN geometry and SEN design, the flow pattern in the mould will also change. It is thus possible to obtain an optimum SEN design if (or when) the desired flow patterns and/or certain predetermined temperature distributions are achieved. Expensive plant trials (downtime for set-up of experiments, tons of scrapped steel should the experiment fail, to name a few possibilities) can be eliminated if accurate and believable[5] mathematical and/or physical models are developed for the SEN and mould flow domain. The most common and reliable mathematical modelling technique is the use of Computational Fluid Dynamics (CFD)[6], especially when the flow path is quite difficult to define analytically and whenever the flow is turbulent (high Reynolds number), rendering classical analytical mathematical modelling almost impossible to solve [9].

Both cases stated above are true when modelling the SEN and mould:

- The geometry is complicated and it is thus difficult to describe the latter and subsequently difficult applying an analytical modelling technique.
- The flow (especially of the jets emanating from the SEN) is highly turbulent; the equations of viscous flow (Navier-Stokes equations – refer to Chapter 2) are thus impossible to solve analytically, because the boundary conditions become randomly time-dependent [9].

Consequently CFD techniques (also known as numerical modelling) will be applied in this study as an inexpensive alternative to genuine plant trials, in order to find an optimum SEN design by applying mathematical optimisation.

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[5] The mathematical or physical model of the plant situation should be accurate and obviously predict the genuine flow situation; otherwise the use of mathematical modelling is obsolete.

[6] CFD: Computational Fluid Dynamics. These techniques comprise:
Discretising the flow path into finite elements, and solving the Navier-Stokes Momentum Equations as well as mass and energy conservation equations (refer to Chapter 2 for more details concerning these equations) for each element (or cell), taking into account the boundary conditions enclosing the flow path. Energy conservation equations are especially important for heat transfer modelling.

Using journal or scripting capabilities of the commercial CFD-package FLUENT's [10] pre-processor GAMBIT [11], the CFD grid generation process can be automated with respect to certain predetermined variables (mathematically stated as the vector $\boldsymbol{x}$) in the SEN design. Examples of candidate variables are the SEN nozzle height, SEN nozzle angle as design variables; and submergence depth of the SEN nozzle as an example of an operational parameter that may also influence the solution. A fully automated set-up thus comprises automatic grid generation for any (predetermined) variable value and any (predetermined) boundary condition variation; and subsequently an optimiser can be linked to this automated CFD parameterisation set-up.

Mathematical optimisation can be applied to real problems (as the optimisation of the SEN design), by identifying a suitable objective function (or combination of objective functions or rather a multi-objective function). As a rule of thumb, the objective function is chosen in such a manner that an optimum solution (thus an optimum combination of variables) will be obtained if the objective function is minimised.

The mathematical optimisation technique applied in this project, is the response surface methodology as implemented in LS-OPT [12][13], which briefly involves the following:

Design response surfaces of the objective and constraint functions are fitted through points in the design space (the full range of all the variables $\boldsymbol{x}$) to form approximate optimisation problems on a sub-design region (a smaller region within the ranges of the variables $\boldsymbol{x}$). These response surfaces are approximated using a linear (or quadratic) approximation for this study. The size of the sub-design region is heuristically adjusted with each design iteration to counteract oscillations due to numerical noise in the optimisation process [13].

The successive response surface of the objective function is minimised using the adapted dynamic trajectory method of Snyman (LFOPC), which uses appropriate penalty function formulations in order to handle constrained optimisation sub problems [14].

An example of an objective function applicable to this problem is to minimise the turbulent kinetic energy on the meniscus surface. Various studies (*e.g.* Refs. [2][4][5]) have linked excessive turbulence on the meniscus (where the slag powder and liquid are found) to quality problems due to the entrainment of slag into the molten steel. For 2D cases in this study, minimising the maximum turbulent kinetic energy on the meniscus is selected as a candidate objective function to evaluate the combined effect of typical SEN design parameters when linked to a mathematical optimiser. The author is aware that an "optimum" SEN design that results from an optimisation study using the minimisation of the maximum turbulent kinetic energy (TKE) on the meniscus surface, may not be an optimum solution. By minimising the maximum TKE on the surface, the focus is on minimising slag entrainment from the meniscus surface, neglecting the possible effect of meniscus freezing **caused** by too low a TKE value. However, for the first 2D study (in Chapter 5, Section 5.2), temperature effects are neglected, which renders meniscus freezing impossible to be determined numerically. Furthermore, in an effort to prevent obvious meniscus freezing in the 2D optimisation study, constraint functions are incorporated to limit minimum meniscus velocity (magnitude) and to prevent an excessively deep jet impingement. Refer to Chapter 5, Sections 5.2 and 5.5 for detail.

Two optimisation approaches or studies are performed in this study: a 2D case (fully automated optimisation) as well as a 3D design exploration case. At first, it was assumed that the numerical CFD solutions are correct and the optimisation study was valid without experimental verification. However, when evaluating the base case (firstly in 3D modelling), it was found that the solution is very dependent on the mesh quality – especially in the high vorticity zones near the jet exits at the SEN ports. In order to validate the CFD solution procedure to be used with all separate CFD evaluations, a 40%-scale mould water model was designed and built by the author. Two base cases were validated with experimental water model results and compared satisfactorily.

The main objective of this study is to design a SEN that will cause desirable flow situations and thus result in good quality steel, by using CFD linked with mathematical optimisation. The design will be achieved by starting off with a base design, which is currently in use at Columbus Stainless, Middelburg, South Africa, and optimising this design by minimising pre-selected multi-objective functions (that represent the selected desirable flow situations and/or boundary conditions). Further objectives include validating CFD results as well as the effectiveness of mathematical optimisation by comparing CFD results (2D and 3D) with 40%-scale water model experimental results. Another objective is to prove that CFD linked with mathematical optimisers (especially parametric CFD-optimisation studies) can be a very valuable and usable tool to achieve significant results (optimal SEN designs). These techniques can be applied by steel plants to design a SEN to suit their needs (different flow situations, plant circumstances and steel grades will necessarily require different SEN designs) without significant production losses due to unsuccessful and costly plant trials.

In the following Chapter, some background is presented to acquaint the reader with the history of steel making and the ultimate development of continuous casting, as well as the importance and influence of the SEN in the continuous casting process.

The design and construction of the 40%-scaled water model is then presented, as well as the verification of the scaled water model with a full-scale water model. Water model results are presented for later comparisons.

Thereafter, it is shown that base case design is the obvious first step in the optimisation process, which is followed by the official formulation of the optimisation problem for this study. The solution of the optimisation problem follows, using 2D and 3D models, where optimum SEN designs are obtained by linking CFD with mathematical optimisation. The base case design as well as an optimum SEN design (from the 3D design exploration case) are validated experimentally using the specifically designed and built 40%-scaled SEN and mould water model.

This dissertation is concluded with a brief conclusion and a description of future work and related topics that arose from this study.