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Heat Transfer Characterization in the Mould of a High Speed Continuous Steel Slab Caster

S.K.Das ,
Mathematical Modelling & Simulation Division
National Metallurgical Laboratory (CSIR)
Jamshedpur 831007
Email: skd@nmlindia.org

K.M.Godiwalla,
Mathematical Modelling & Simulation Division
National Metallurgical Laboratory (CSIR)
Jamshedpur 831007
Email: kmg@nmlindia.org

S.P.Mehrotra
Director
National Metallurgical Laboratory (CSIR)
Jamshedpur 831007
Email: spm@nmlindia.org

Abstract

The understanding of the heat transfer behaviour in the mould during continuous casting (CC) operation has been indispensable throughout the development of the high-speed casting process. While plant trials showed rate of increase of sticking breakouts during high speed casting , heat transfer models have been increasingly applied for developing fundamental understanding of the mould behaviour and causes of such breakouts. The paper encompasses some of the analytical studies undertaken on the basis of mould heat transfer analysis and modelling of plant data to characterise the thermal behaviour of the high speed mould and associated heat transfer constraints for casting at higher speeds. Some of the important aspects of mould phenomena have been considered such as the effect of mould flux on heat transfer, heat transfer response of the mould under high speed casting conditions and mould flow dynamics. It is observed from the technological view point that, redesign of the mould may often be necessary to comply with heat transfer requirements if sustained high speed casting need to be pursued.

1. Introduction

Continuous casting (CC) process particularly in the steel industry has made rapid strides in the last three decades. Over 95% of the steel products produced in Japan are through this route. The same trend has been observed in the rest of the world as well. Continuous casting technology has advanced due to innovations resulting from knowledge gained from several technical investigative tools. These include expensive plant trials, laboratory experiments, water models, and mathematical models. As the process becomes increasingly optimized and mature, simple trial and error is less likely to lead to success. At the same time, these trials become more costly, as more statistics must be gathered to quantify success. It is therefore important to have a correct understanding of the fundamental phenomena that occur in the process. Ideas which grow from deep understanding are more likely to lead to the successful trials and technology advances of the future.

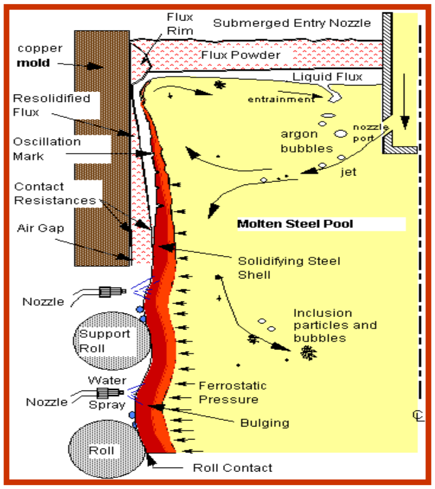

Fig. 1-A Mould and sub-mould processes

The historical origins of continuous casting have been observed in billet machines, beginning from the inception of the continuous casting process to the groundbreaking technologies that have made the process both viable and successful. Subsequent breakthroughs in process control and mould design have allowed higher casting speeds to be achieved. There have been many studies that have documented the response of the mould at conventional casting speeds; however, relatively few comprehensive studies have been conducted at casting speeds exceeding 1.5 m /min for slabs under Indian conditions , and even fewer high speed studies that have used instrumented moulds. The paper provides an assessment of the mould heat transfer phenomena with increased casting speed, using data gathered from literature and modelling. The emphasis is on the heat transfer characterisation of the casting process, focusing on the effect of casting speed on the heat transfer in the primary cooling zone.

The last few decades witnessed a rising trend towards increasing the casting speed of continuously cast strands, in order to raise the productivity of machines [1,2,3]. Enhancement of casting speeds to higher than about 1.5 m/minute places stringent requirements and control on the mould lubrication, heat transfer and hydrodynamics. For slab casting, mould powders are employed for lubrication. Any deficiency in the lubrication, i.e., increase in the friction between the mould wall and the shell of solidified strand, and non-uniform heat transfer give rise to surface defects, as well as break-outs due to rupturing of the shell. Fig 1-A shows the schematic of mould and sub-mould phenomena

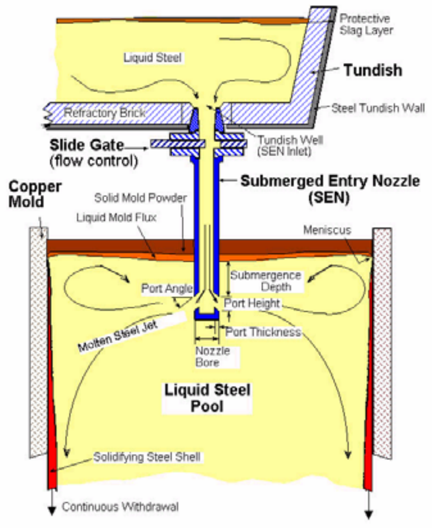

Fig. 1-B Schematic of tundish-mould operations

2. Mould heat transfer

The mould is the “heart” of the caster; it is the primary heat-extraction device whose functions are to extract superheat from the liquid steel, to grow a solid shell of sufficient thickness to contain the liquid pool below the mould without break-outs and to support the shell during its initial growth. The design and operation of the mould, which governs heat extraction, profoundly affects surface and even internal quality. Heat transfer is a primary factor in the quality of the cast structure. The understanding and control of the heat transfer in the primary cooling zone is essential in the prevention of cracks, promotion of uniform shell growth, and control of the cast structure. Higher casting speeds lead to higher heat transfer - rates, particularly in region below meniscus.

Heat transfer in the continuous slab-casting mould is governed by many complex phenomena. Figure 1-B shows a schematic of some of tundish - mould operation. Liquid metal flows into the mould cavity through a submerged entry nozzle and is directed by the angle and geometry of the nozzle ports[1]. The direction of the steel jet controls turbulent fluid flow in the liquid cavity, which affects delivery of superheat to the solid/liquid interface of the growing shell. The liquid steel solidifies against the four walls of the water-cooled copper mould, while it is continuously withdrawn downward at the casting speed. Mould powder added to the free surface of the liquid steel melts and flows between the steel shell and the mould wall to act as a lubricant[2], so long as it remains liquid. The re-solidified mould powder, or “slag,” adjacent to the mould wall cools and greatly increases in viscosity, thus acting like a solid. It is thicker near and just above the meniscus, where it is called the “slag rim.” The slag cools rapidly against the mould wall, forming a thin solid glassy layer, which can devitrify to form a crystalline layer if its residence time in the mould is very long.[3] This relatively solid slag layer often remains stuck to the mould wall, although it is sometimes dragged intermittently downward at an average speed less than the casting speed.[4] Depending on its cooling rate, this slag layer may have a structure that is glassy, crystalline, or a combination of both.[5] So long as the steel shell remains above its crystallization temperature, a liquid slag layer will move downward, causing slag to be consumed at a rate balanced by the replenishment of bags of solid powder to the top surface. Still more slag is captured by the oscillation marks and other imperfections of the shell surface and carried downward at the casting speed.

The thickness and shape of the solid shell in the mould and at the mould exit directly affect the possibility of the fatal ‘‘breakout.’’. Besides the heat transfer between the mould wall and solid shell, the temperature distribution inside the cast strand also has a great effect on the thickness and shape of the solid shell. This means that the shape of was the solid shell could be controlled by changing the temperature distribution in the melt pool.. The rate of heat transfer across the interfacial gap depends mainly on the properties of the mould flux filling the gap. These properties include phonon and photon conductivity, radiative properties such as emissivity and absorption coefficient , and contact resistances, especially where the flux is solid.

The composition of the powder should be such that any reaction product with the molten steel being cast, does not affect the properties of the slag formed by the powder, viz. alteration of viscosity and the crystallisation temperature. For example, iron oxide in the mould powder reacts with aluminium in the steel to form alumina, which results in the increase of both the crystallisation temperature as well as viscosity. The obvious result of this reaction is the decrease in its lubricating properties.

It has been observed, in practice, that increase in the casting speed decreases the rate of consumption of mould powder (kg / ton). Higher crystallisation temperature of the powder results in lower heat transfer rate in the mould, similarly higher viscosity powders were found to reduce the heat transfer rates in the mould. Generally a thick glassy slag film forms on the shell side, whilst a crystalline layer forms on the mould side. Powders, which tend to form a large proportion of pores during crystallisation, were found to result in reduction of heat extraction from the solidifying strand. The development of mould powders for high speed casting, therefore, has to be planned carefully, taking into consideration, grade and temperature of molten steel, the casting speed, reactivity of alloying elements with the constituents of the slag.

The quality of con-cast products is affected, apart from the type of mould powder, by the design of the submerged entry nozzle (SEN). The importance of this aspect cannot but be overemphasised, due to its synergistic effect on solidification, defects and surface finish of the product. Experiments and mathematical model based computer simulations indicate that, even a slight off-centre SEN results in periodic, oscillatory flow patterns of liquid inside the mould. This effect can cause uneven solidification and uneven distribution of mould powder for lubrication of the mould. Eddy current measurements indicate the presence of long and short period surface wakes at the meniscus in the mould. The former have frequency of the order of 0.1 Hertz, whilst the latter are about 1.0 Hertz. Comparison of surface velocity at the narrow face of the mould shows that the magnitude is much greater in the case of high-speed casting vis-à-vis low speed casting. At the narrow face of the mould, there is an optimum level fluctuation for the long period wave which causes minimal entrapment of mould powder, and hence lower level of slag inclusions in the product. In addition, this optimal level also reduces irregularities in solidification at the meniscus and also ensures uniform distribution of argon bubbles near the SEN.

Design improvements of CC machine for higher casting speeds necessitates knowledge of coupled multi-physics phenomenon such as, strength of materials, CAD/CAM, fluid flow, heat transfer, electromagnetics, chemical kinetics, thermodynamics, solidification, deformation and creep behaviour of materials and automatic control system analysis. Modern CC machines are equipped to cast over 20 heats in a sequence. This places heavy demand on the operator, tundish refractories and various shrouds, slide gate systems. In the case of slabs and blooms, on-line width adjusting devices have been incorporated. It is even possible to cast, grades ranging from low carbon, medium carbon and alloy steels sequentially in consecutive heats. To enhance productivity, the Japanese steel plants have increased the casting speed of slabs from the earlier range of 0.8 - 1.2 metre/min to over 2.0 metre/min. Existing designs of CC mould can cause problems during casting of steel at higher speeds. This is due to the increased heat flux which results in higher hot face mould temperatures, which, if exceed 350^0 C can cause strand to mould sticking, as well as mould distortion. Redesign and installation of mould is often necessary. Changes generally include thinner wall thickness of plates, larger number of cooling slots and higher surface velocity of water. It is necessary, of course, to adjust other parameters such as the flow conditions prevailing in the mould as well as composition of mould powder in order to effect quality of products at higher casting speeds. Some of the required conditions to facilitate smooth operational stability for high-speed slab casting can be enumerated [4-6] as follows.

1. Enough and uniform thickness of the steel shell at the bottom of the mould in order to prevent bulging and breakout.
2. Sufficient lubrication provided by the powder slag to reduce the friction force between the solidifying shell and the mould wall.
3. The need of cast strands free from defects, e.g. inclusions of entrapped mould powder.
4. Precise control of meniscus level and optimum design of submerged entry nozzle for prevention of powder slag entrapment.

3. Mould Lubrication

In the continuous casting process, mould powders are added to the mould and perform several functions. It is generally accepted that the physical properties of the mould powders used have a significant influence on the surface defects originating in the mould. The breakouts (BO) is one of the major problems in the continuous casting operation, and it is well known that the frequency of the sticking type BO increases at high casting speeds. This BO comes from the sticking of the mould and the solidifying shell due to the increase of friction resistance between the mould and the shell. It is presumed that the sticking type BO is caused by the operational defects as described below [7,13,16]:

- The sudden fluctuation of the molten steel level.
- The reduction of the molten steel flow due to Al_2O_3 build-up clogging the nozzle mouth.
- Unsuitable shape of the nozzle, which results in undesirable patterns of fluid flow.
- Excessive immersion depth of the nozzle.

It is true, of course, that the physical properties of the mould powder also have an important effect on the occurrence of the sticking type BO. The viscosity and the crystallisation temperature of the mould powder have a close relationship with the lubricating function of the powder. The composition of these powders is CaO - Al_2O_3 - SiO_2 system and alkali metal oxide, fluoride and carbon are added, as with traditional powders. Fig.1 shows the influence of basicity on crystallisation temperature for high speed casting mould powders. Some of the powders have been used on trial at the high-speed slab casting machine for low carbon Al killed steel [12, 15,16] to evaluate the consumption rate, surface defects and uniformity of flow. In the high speed casting the heat transfer rate in the mould should be controlled to prevent the bulging of the slab at the mould exit and facial cracking. Many reports concerned with the heat transfer rate in the mould have been published and it is well known that heat transfer is affected by the powder viscosity. Fig.2 depicts the relationship between powder consumption and viscosity of powders at high speed casting (at 1.8 m/min).

These viscosities and crystallization temperatures of the powder were compared with the frequency of occurrence of the sticking type BO. The four mould powders have been tried at the same slab casting machine for low carbon Al killed steel at 1.2 ~ 1.6 m/min.. The mould powders with a high crystallization temperature showed a high frequency of the sticking type BO This results suggests that the crystallization temperature has some influence on the lubricating function of the powder slag. On the other hand, the viscosity of the mould powder showed no influence in this investigation, which may be due to the small range of viscosities of the four powders. From this analysis, it can be concluded that the regulation of the crystallization temperature in addition to the viscosity is required to prevent the sticking type break-outs. Another approach to the prevention of the sticking type break-outs is to increase the absolute amount of powder slag flowing in to the meniscus. Increasing the powder consumption rate is also important for the prevention of slag spot on the strand surface. Generally, the powder consumption rate decreases with the increase in casting speed .

Experiments were reported on an instrumented mould using with thermocouples to measure thermal characteristics and with load cells to measure frictional characteristics at the copper-steel interface [9]. The thermocouples were located 16 mm from the hot face at various distances from the top of the copper and were symmetrically placed with respect to the water slots to simplify thermal analysis. The sheaths were located in 2 mm diameter holes drilled vertically in the copper and the hot junction tips were cemented in place with high temperature thermally conductive epoxy. One set of thermocouples was located at the centre of the wide face and the other set was at 525 mm off the centre-line, roughly at the quarter point of the full-width mould. Temperature readings were taken at one-second intervals. Temperature profiles, from the top to the bottom of the mould, were analysed. It has been observed that there is a steep rise in temperature at the bottom of the mould, which is probably caused by increased contact of the steel shell with the copper due to the increased ferro-static pressure at the bottom of the mould. As was noted earlier, the primary shortcoming which is normally responsible for heat transfer problems during sustained high-speed casting was excessively high mould copper hot face temperatures.

It has been reported that excessive copper surface temperatures increase the risk of sticker-type breakouts. While plant trials showed no rate of increase of sticking breakouts in high speed casting some thermal models were studied for calculation mould surface temperature. The thermal model used the measured temperatures from the instrumented mould thermocouples. The two-dimensional heat conduction thermal model have been used to analyse a horizontal slice of the copper mould and to determine hot surface temperatures and heat transfer coefficient, heat fluxes and water channel temperatures. For these calculations the heat transfer coefficient during high speed casting at the water channel interface have been computed from established relationship [11,12]. To verify the validity of the two-dimensional model in the region of the meniscus, heat fluxes determined with the horizontal model were used as boundary conditions in a vertical model of the mould. The temperatures estimated from the vertical model at the thermocouple locations were in close agreement with the measured temperatures, thus, indicating validity of the horizontal model. The isotherms range in the mould from 329^0 C near the hot face to 83^0 C near the root of the water channels. The slight asymmetry is due to the increased channel pitch required by the bolt-holes. Fig. 3 shows the effect of heat flux on measured hot face and water channel temperatures and hot face heat transfer coefficients have been obtained from the model. The instrumented mould has proven to be a valuable tool for understanding the mould phenomena during high speed continuous casting. Extensive additional experimentation will be required to develop a better understanding of mould powder characteristics and thermal behaviour of the mould also to develop operating practices for casting specific grades. Fig.4 shows the heat transfer coefficient (centreline) as a function of casting speed. The potential for detecting crack formation through friction force measurements and heat transfer analysis should be studied in greater detail for parametric optimisation during high speed casting.

Redesign of the mould was, therefore, necessary if sustained high-speed casting is to be pursued as a means of increasing caster productivity. A mould for high-speed casting was designed, fabricated and put into service. These plates were designed with thinner working copper and increased number of water slots and higher water velocity, all aimed at reducing the surface temperature[14,15]. In addition, the copper is a Cr/Zr alloy to reduce distortion during casting and the lower half of the mould is Ni coated to increase the wear life. It may be noted that the thinner working thickness for the high-speed plates, 20mm is required in place of 30mm thickness for the standard design. There are more slots for the high-speed plates, the slots are thinner and the water velocity is greater than for the standard design. The narrow faces of high-speed mould were also designed with thinner working copper and a smaller cooling channel pitch. In order to verify operation of the plates for the high-speed mould, it is imperative to conduct measurements of the copper temperatures, model the copper plates and calculate the expected maximum surface temperatures. Fig.5 shows heat flux profile for low carbon steel as a function of distance from the top of the copper with a typical mould powder at a casting speed of 2.0 m/min.

4. Mould hydrodynamic behaviour

Fluid flow condition in the continuous casting mould has a large influence on the heat transfer, solidification, quality and productivity of the slab caster. The flows at the free surface are particularly important as it is in this region that initial solidification occurs. Free surface fluctuations prevent the formation of a uniform mould flux layer, adversely affecting the uniformity of lubrication and heat extraction. These factors can lead to sticking of the strand in the mould, uneven oscillation mark spacing and depth, and the formation of longitudinal cracks. When casting speed is increased which leads to significantly higher flow velocities in the mould. Problems associated with meniscus stability, free structure fluctuations and mould flux entrapment may therefore be more severe. The restricted mould cross-section further exacerbates these problems by constraining submerged entry nozzle (SEN) dimensions. The interaction between the confined jets and the re-circulating fluid eddies could be a critical factor responsible for the oscillation in the thin slab flow system. The specific geometry and the existence of the two SEN jet streams contribute to the period and amplitude of the oscillation, which is complex to analyse mathematically. A one jet system in a simple geometry was used to explore and demonstrate the inherent features of confined jet oscillations.

To increase the productivity of continuous slab caster, high-speed casting is necessary. But high-speed casting sometimes has problem of mould level fluctuation and mould powder entrapment. To prevent mould powder entrapment, which causes the surface defect of slab, the techniques of precise control of meniscus level in mould is imperative. In spite of this precise control at high-speed casting, the number of slab surface defects caused by mould powder did not always decrease. An analysis has been made to investigate the flow pattern of molten steel in mould at high-speed casting such that necessary strategy should be devised to prevent mould powder entrapment at higher speeds.

It has been observed from reported model studies that the fluid flow condition in the slab caster water model was neither steady nor symmetrical, and instead oscillated periodically[10].The oscillation was sustained and periodic, because of narrow face surface movement with respect to time for a full-base

SEN. The sub-surface velocity and surface movement data had similar waveform and magnitude, with a small time lag. The inertia of the up-welling flow near the narrow face was obviously responsible for the rise of the free surface and the magnitude of the surface waves. Fourier analysis of the time series wave height data reported in literature which shows that primary frequency of oscillation of 0.2 Hz, or a period of 5s are present. There was also a small peak at 0.7 Hz, which corresponds to the natural frequency for gravitationally induced waves in this geometry. The increase in maximum wave height observed as a function of casting speed is shown in Fig. 6 for the range of dimensions of the full-base SEN configuration. Increasing the downward jet angle by cutting away the base of the SEN decreased the maximum wave height, and caused significant changes to the flow behaviour. This was particularly true for the special case of the straight through SEN, which produced only one jet stream into the mould [17-20]

This is an important information, which gives an idea regarding the order of magnitude of surface wave amplitude as a function of increased casting speed. Enhanced downward flows were observed with the shortened base and straight through SEN configurations.

4.Conclusion

In order to facilitate high speed continuous casting of steel (over 1.5 m/min)under Indian condition, a well instrumented mould is a prerequisite for monitoring the optimal set-points of process parameters in order that sustained trouble-free operation is ensured for increasing caster productivity. A well instrumented mould would require about 30 thermocouples to be installed on each of the wide faces, as well as about 6 numbers in each of the narrow faces, along the width and height of copper. The utility of the mould thermal monitoring system is to facilitate improvement in the mould operation, not only from the perspective of breakouts but also for ensuring surface quality. Redesign of the mould may also be necessary if sustained high speed is planned to be pursued. The design of wide and narrow face copper plates have to be improved with thinner wall thickness of mould and increasing the number of water channels together with increase in the water velocities. In high speed casting the magnitude and uniformity of heat transfer from the steel shell is dictated overwhelmingly by the slag film at the interface between the steel and copper plate. Variation in the thickness of the copper plate or in the flow rate of the mould cooling water have only marginal influence on heat flux, however, have significant affect on the mould hot face temperature, certain grades of steel, particularly those falling into the peritectic grades are more susceptible to surface defects and breakouts. It is important, for these grades, in particular, that the heat transfer conditions in the mould are stable and uniform around the entire perimeter of the mould. The technological challenges of high speed casting for the steel industry in the country can be adequately addressed and surmounted, if there is a concerted effort from academia, R&D organization and steel industry to create a synergy and strategic alliance to address various multi-disciplinary issues.

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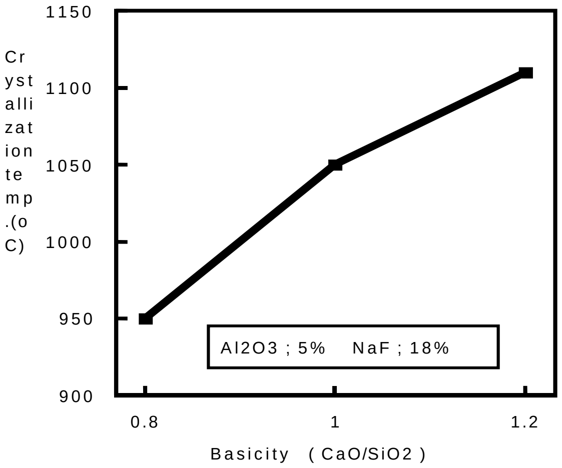

Figure 1 - Influence of CaO/SiO2 on Crystallisation temperature.

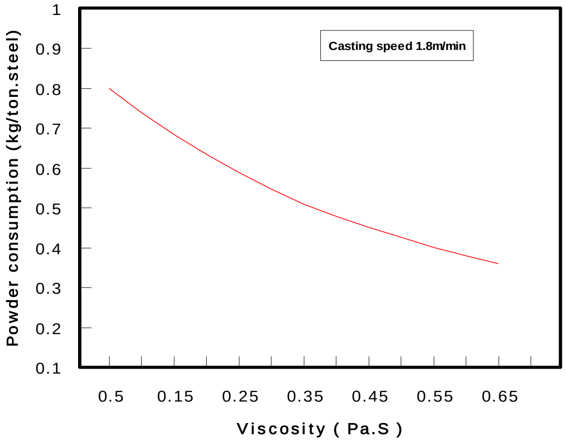

Figure 2 - Relationship between powder viscosity and powder consumption

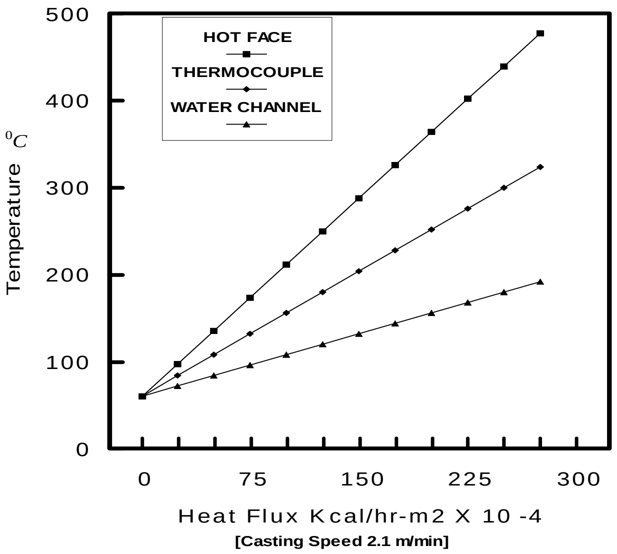

Figure 3.- Mesured and calculated teperature as a function of heat flux during high speed casting

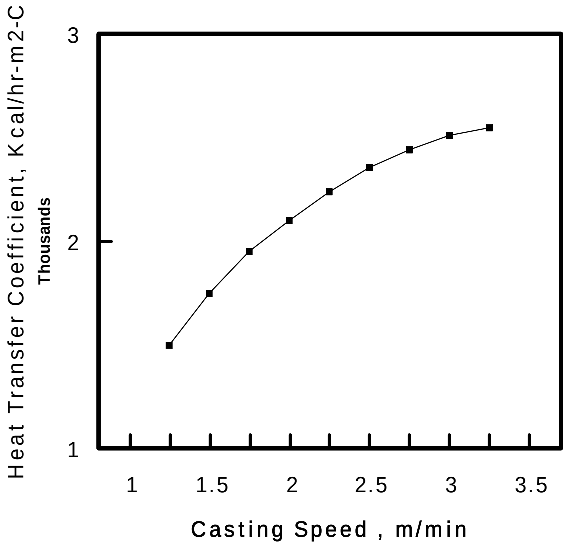

Figure 4 - Hot Face Maximum Heat Transfer Coefficient (Centreline) as a function of casting speed

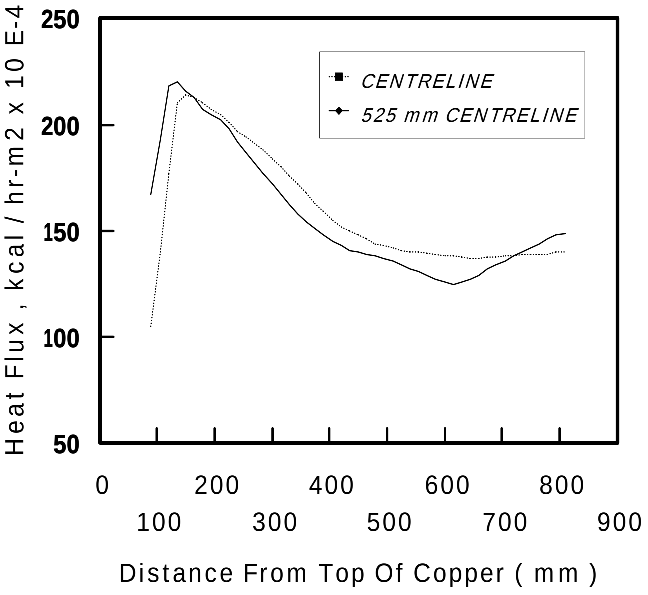

Figure 5 - Predicted heat flux for low carbon(<0.08%) steel with mould powder (E) and casting speed of 2.0 m/min

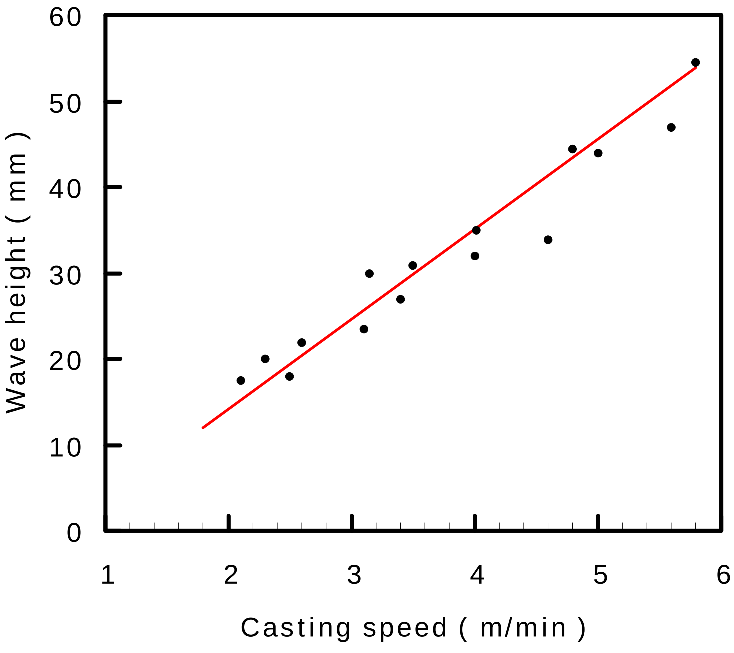

Figure6 - Effect of casting speed on wave height for a standard SEN (Submerged Entry Nozzle)