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HIGH SPEED CONTINUOUS SLAB CASTING OF STEEL — PROSPECTS AND PITFALLS

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ABSTRACT

After Oxygen steel-making, continuous casting (CC) is undoubtedly the most important technological advance, specifically for the steel industry during the post-war period. Although there are many differences of details, the general engineering design principles of continuous casting machines are reasonably well understood. It is clear that, to enhance the productivity of CC process by increasing the casting speed; a large number of technological problems involving mould lubrication, fluid flow, meniscus stability, mould oscillation, mould flux entrapment, heat and mass transfer, and solidification are required to be solved at the mould level. The trend in India, of late has been to increase the productivity through increase in the average casting speeds for slabs from approximately 1.0 metre / min to over 1.5 metre/min. This has been a technological challenge in this new millennium. Another important recent trend in the steel industry is the development of processes for casting steel closer to the final product size. The continuous casting of thin slabs (ranging 20~60 mm thickness and 1500~2000 mm width) allow hot-direct rolling to be performed in line with a conventional finishing mill, eliminating the need for a roughing train. This advanced continuous- casting technology of thin slabs is growing in the steel industry owing to the associated savings in capital cost, energy, and manpower. Increase in casting speed in high speed casting of steel slabs including thin slab casting, however, may in all likelihood aggravate problems of product quality. This encompasses effect of mould flux on heat transfer, characterisation of mould powder for high speed casting, thermal and lubrication behaviour of the mould under high speed casting conditions, dynamic melt flow behaviour and wave generation in the mould with increased casting speed, effects of SEN (Submerged Entry Nozzle) design on melt flow characteristics, meniscus level fluctuation and Electromagnetic control for meniscus stability.

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. In India CC was initiated by the mini steel plants established in the 1960s, whilst the integrated steel plants could install the same only in the late 1970s, due to their large investments in the ingot-teeming and rolling mill complexes during the 1950s and 1960s. A large number of mini steel plants in the country now have billet casters, whilst the integrated steel plants of RINL, SAIL and TATA STEEL have billet, bloom and slab casters. Up to the 1980s much of the CC cast products were restricted to plain low and medium carbon steels. However, at present, high carbon steel for wire rod, free cutting steels, HSLA, weathering, alloy and other steels are being routinely produced. Attempts are also being made to cast certain difficult grades such as the peritectic grade.

Although the continuous casting of steel was attempted by Sir Henry Bessemer in 1860s, by cooling molten steel between two water-cooled rolls, it was only in the 1950s through the efforts of Soviet technologists that the concept could be commercialised. Initially the products were cast vertically in the form of billets on a semi-continuous basis. Several designs of the CC machines exist, which include belt type, roll type, tube casters, horizontal bar casters, and the large tonnage curved strand casters for steel. The advantage of CC over the conventional ingot-rolling mill is obvious. The foremost is being considerable conservation of energy. Savings also accrue in the form of lower capital investment costs as well as increased productivity and yield due to lower crop rejections, which are inherent in the ingot-processing route. However, in certain cases such as manufacture of large forgings for shafts and pressure vessels, the ingot casting route is inevitable. Now, attempts are being carried out to commercialise the production of near net-shape products such as thin strip, thin slab etc, the primary goal being to achieve metallurgical and chemical homogeneity in the thin as-cast section at rapid solidification rates. Products of thin slab casters are in the range of 20 to 60 mm thicknesses and 1500 to 2000 mm width. The increasing popularity of thin slab casting techniques over the conventional casting techniques are due to savings in energy due to elimination of slab cooling, conditioning, stocking, reheating and roughing operations of conventionally cast slabs, production in smaller tonnages of various steel grades and quality, lower operating costs and capital investment in the production of flat rolled products and less space and man power requirements [17].

The comparison between these two process routes and the pictorial view of the thin slab caster have been given in Fig. 1 and Fig. 2 respectively.

After the introduction of Compact Strip Production (CSP) by SMS Schloemann Siemag (today SMS Demag), the start of the first CSP plant followed in 1989 at Nucor Steel, Crawfordsville, IN, USA. Plantengineering and the degree of automation together with caster productivity and metallurgical results have since then been developed further so that today practically only thin slab casters are being considered for installation. At present, some 35 thin slab plants are in operation or scheduled world wide, of which 25 are CSP plants. With the start-up of the Terni CSP plant in Italy, thin slabs are also used for stainless steels. By increasing casting speed to above 6 m/min and by extending plant utilisation time, the annual production volumes have been continuously increased. Today, the standard achieved with regard to product quality and output in CSP plants can be compared with those of integrated steel plants. An essential prerequisite here is the funnel-shaped mould, the pictorial view of which is given in Fig. 3.

India's first thin slab caster started up in April, 1998 by Ispat Industries Ltd., Dolvi near Mumbai and now Tata Steel has included a thin slab caster in its expansion plan. The different types of thin slab casters are described as follows.

TYPES OF THIN SLAB CASTERS

Stationary mould thin slab casters:

Out of different categories of thin section casters, the stationary mould and belt casters are primarily suited for casting of thin slabs. In 1985, SMS Schloemann-Siemag had begun extensive pilot plant casting of thin slabs 40 to 50 mm thick, up to 1600 mm wide at speeds of 5 to 6 meters/min, at the SMS foundry in Kreuztal, West Germany. The unique feature of this thin slab caster is the funnel-shaped stationary mould with a specially contoured submerged nozzle to prevent steel reoxidation and to facilitate solidification of a strand shell with low transverse stresses. Inductive or radioactive measuring systems are used to detect and correct the small liquid steel surface area fluctuations. High casting speeds (6meters/min) of this caster require oscillation frequencies of over 400 cycles/min and stroke lengths of 4 to 8 mm. The desirable properties of the mould powder used here are low viscosity and low temperature.

Mannesmann Demag Huettentechnik (MDH), in cooperation with Mannesmannroehren-Werke (MRW) and Mannesmann Rohstoffwerke (MRO), had developed a new continuous caster producing thin slabs of 40 to 70 mm thick and 1200 mm wide. The salient features of this machine includes,

- Narrow submerged nozzle and vertical curved mould with parallel broad faces that guide the strand vertically in the upper part of the mould and tangentially at the lower mould region.
- Adjustable mould width.
- Casting speed up to 6 meters/min with a casting rate up to 3 tonnes/min.

Twin-belt thin slab casters :

The Hazelett twin-belt moving mould caster produces non-ferrous thin slabs up to 38 mm thick. The advantage of this system is that it has a frictionless mould and therefore, does not impose the casting speed limitations inherent in a stationary mould system. There are number of industries who used the principle of this twin-belt caster in developing thin steel slab casting techniques. Nucor had installed a 1300 mm wide Hazelett caster with casting thickness of 38 mm.

Horizontal thin slab casters:

Kawasaki's experimental twin-belt caster (KCC) has been developed by Kawasaki Steel for producing thin slabs of 30 mm thick and 100 to 150 mm wide. Maximum withdrawal speed here is 12.5 meters/min. This caster consists of a specially designed nozzle connected to a molten steel reservoir.

British Steel Corp. had installed a 0.5 tonne steel plant at the Teesside laboratories for casting thin slabs up to 25 mm thick and up to 200 mm wide. This caster consists of a moving train of hematite iron mould segments which form a 15 meter long trough. 500 mm wide and 75 mm deep. This produces with a casting rate of 5 tonnes/min.

Another experimental thin slab horizontal caster, developed for the horizontal casting technology for billets, is in operation at the research laboratory of Steel Casting Engineering Inc., Orange, Calif. A thin section, 15x150 mm, has been cast at 2.5 meters/min.

Technological ramifications of high-speed casting

The last decade has witnessed a rising trend towards increasing the casting speed of concast strands, in order to raise the productivity of machines [1,2,3]. 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. Fig.4 shows the schematic of tundish-mould operation. 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. Fig.5 shows a schematic of mould and sub-mould processes. 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 denitrify 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.

Enhancement of casting speeds to greater than about 1.5 m/minute places stringent requirements and control on the mould lubrication. 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, gives rise to surface defects, as well as break-outs due to rupturing of the shell. The two most important parameters characterising the performance of mould powders are:

a) crystallisation temperature

b) viscosity at the temperature of operation in the mould

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.

The modern CC machine is an epitome of a number of frontier technologies in fluid and thermal engineering, control system synthesis, machine design, machine dynamics, industrial tribology, refractories, sensor development, non-destructive evaluation. Design of this system involves knowledge of coupled phenomenon of 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 3500 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.

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 herewith [7,13,16]:

i. The sudden fluctuation of the molten steel level.

ii. The reduction of the molten steel flow due to Al2O3 build-up clogging the nozzle mouth.

iii. Unsuitable shape of the nozzle, which results in undesirable patterns of fluid flow.

iv. 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 physical and chemical properties of some newly reported powder are shown in Table I. The composition of these powders is CaO - Al2O3 - SiO2 system and alkali metal oxide, fluoride and carbon are added, as with traditional powders. Fig.6 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] 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 report-concemed 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.7 depicts the relationship between powder consumption and viscosity of powders at high-speed casting (1.8 m/min)

With reference to Table-I, for powders E and F which had been used for casting speed up to 1.8m/min., the consumption rate was less than 0.30 kg/m2 at casting speed of 1.8 m/min. Judging from reported information, this consumption was insufficient for high speed casting. Powder G, H and I were satisfactory in this respect, however, some corner cracks appeared in powder G. It can be inferred that the very low crystallisation temperature of powder G resulted in a high heat transfer rate and an excessive cooling in the slab. In the next place, the mould temperatures in use of powder H and I were reported to be continuously measured by means of setting the thermocouples to a depth of 8mm from the mould surface to compare the uniformity of flow of both powders.

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.

Heat Transfer characterization

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

Table I Characteristics of Mould Powder

	Chemical Composition (%)							Physical Properties		
	SiO_2	Al_2O_3	Fe_2O_3	CaO	$*R_2O$	F	FC	Softening Temp. (°C)	Viscosity at 1300°C (Poise)	Crystallization Temp. (°C)
E	30.0	7.6	2.0	29.9	15.0	10.0	3.9	1060	1.0	1080
F	34.6	5.3	0.2	29.7	13.2	7.8	4.7	1005	1.5	1010
G	31.4	5.1	0.3	24.6	17.7	5.5	4.5	850	1.1	890
H	33.8	3.8	2.0	30.8	16.3	5.2	3.4	900	0.8	945
I	31.7	5.7	0.3	29.0	14.2	8.2	2.8	930	0.9	980

$*R_2O = Na_2O + Li_2O + K_2O$

3. Mould Heat Transfer

The understanding of the thermal behaviour of the mould during CC operation has been indispensable throughout the development of the high-speed casting process. 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

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]. Water flow conditions in the mould used for the calculations are given in Table 3.1. 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 3290 Cnear the hot face to 830 C near the root of the water channels. The slight asymmetry is due to the increased channel pitch required by the bolt holes. Fig. 8 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.9 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 highspeed casting.

Table II Thermal Analysis of Wide Face Mould Copper Plates

	Standard Casting Mould	NKK No.5 Caster (Comparison)	High Speed Casting mould
Slot Size, mm	25x9	15 x 5	25x5
Slot Pitch, mm	35	20	28.75
Copper Thickness, mm	55	40	45
Water Flow Rate, l/min	5,100	-	5,100
Water Velocity, m/sec	5.5	9.0	9.3
Heat Transfer Coefficient For water, Kcal/hr-m2-c	19,500	34,150	34,600
Copper Type	Ag	-	Cr/Zr
Water Temperature, C	38	38	38
Steel Temperature, C	1,554	1,554	1,554
Thermocouple Distance From Hot Face, mm	16	8	20

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.10 shows a computer model based predicted 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.

Since, the high speed plates have less thermal resistance it would be expected that the heat removal rate would be greater than with the standard plates. At any local position in the mould the ratio of heat fluxes for the two moulds is given by,

$$\frac{F_2}{F_1} = \frac{1/h_1 + W_1}{1/h_2 + W_2} \quad (1)$$

Where F is the heat flux Kcal/hr-m^2, h is the hot face heat transfer coefficient, Kcallhr-m^2 -C, and φ is the thermal resistance of the copper and water channels hrm2 -C/Kcal. Subscripts 1 & 2 represent the standard and high speed copper plates respectively. The thermal resistances are a function of the copper geometry, copper thermal conductivity and water side heat transfer coefficient and are found from thermal analysis of the standard copper plates on the basis of analytical studies. For example, to determine the ratio of the fluxes at the upper half of the high-speed mould, equation (2) becomes:

$$\frac{F_2}{F_1} = \frac{1/h_1 + 1.60 \times 10^{-4}}{1/h_2 + 1.07 \times 10^{-4}} \quad (2)$$

It may be inferred that the mould powders for high-speed casting require superior lubricating function. The sticking type BO has a close relationship with the powder properties, especially the crystallization temperature. High crystallisation temperature will cause the sticking type BO. In general, the consumption rate decreases in high-speed casting, consequently the possibility of the sticking type BO. increases. The proper consumption rate can be insured by the adjustment of the softening temperature and the viscosity. The heat transfer rate in the mould is affected by the viscosity and the crystallisation temperature of the powder slag. Excessive heat transfer causes surface cracks on the slabs. The pores in the crystallised powder slag may playa role in the resistance to heat transfer. Since the heat transfer in the high-speed mould is reasonably complex, it cannot be fully analysed without a more detailed investigation both theoretically and experimentally.

DYNAMICS OF MOULD FLUID FLOW

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.

Effects of high casting speed on surface fluctuation

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 subsurface 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. 11

for the range of dimensions of the full-base SEN configuration. 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. 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.

Oscillation behaviour of meniscus level:

Standing waves, at the natural frequency, although not dominant did occur in the water model and are consistent with the short period waves [8]. The dominant longer period waves in steel and water cannot be explained in this manner, but rather must be due to the dynamics of the jet flows in the mould. Fluid enters the mould as one or more jets which are confined by the mould plates and the free surface. The effect of the confining walls is to cause the fluid in the mould cavity to recirculate. Such systems are known to result in oscillatory flows and this was explored as the potential mechanism for oscillation of mould flow at higher casting speed.

Comparison of the periods of oscillation for the 1/6th and full scale water models [7] demonstrated that the oscillation period could be scaled according to the Strouhal number, which is a non-dimensional frequency used to describe the behaviour of time dependent flows, expressed as;

$$St = \frac{f \times L}{u} \qquad (3)$$

Where, u is the surface flow velocity, f is the frequency of oscillation and L is the reference length. This suggests that a correlation should exist between the flow rate, the volume of fluid involved in the oscillation, and the period of oscillation. For a two jet (twin port) SEN configuration, the upper recirculating region was responsible [8,10] for the oscillation. In this case, the volume in the mould to the bottom of the SEN was taken as the active volume. For the straight through SEN, the entire fluid volume of the model was shown to be the active volume.

The theoretical flow solution (Fluid dynamic analysis) [18] has been examined to identify the mechanism of the oscillation. The mechanism is divided into a sequence of steps and outlined in the following paragraph. The jet angle was defined as the angle to the vertical made by the velocity vector immediately below the nozzle exit. A positive jet angle indicated that the jet had bent toward the right hand side of the cavity. Pressure was calculated at the centre of each of the re-circulating eddies. The vertical component of momentum of the re-circulating flow was calculated by integrating along a horizontal line through the flow domain at the level of the nozzle discharge. Table V shows comparison of predictions of fluid flow mathematical model and measurements from physical model experiments for oscillation periods.

Table V. Comparison of physical and mathematical results for meniscus oscillation period [17]

Inlet velocity	Jet Reynolds number	Oscillation period, (see)	
m/s		physical model	mathematical model
5.04	35 780	2.5	2.77
6.30	44100	1.8	2.21

At high casting speed, there is a threshold surface stream velocity for the entrapment of mould powder slag. The existence of such threshold velocity has been confirmed by water model experiments [10]. Direct measurement of surface stream velocity in a mould is difficult. It is reported that from eddy current measurement for high speed level fluctuation at the narrow face side of the mould is greater than 10 mm, however level fluctuation at a quarter width point where a level sensor for slide gate control is located was less than 5 mm. The level fluctuation at the meniscus at high casting speed represented mainly the balance between pouring rate of molten steel and discharging rate of strand, on the other hand the level fluctuation at narrow side represented mainly the intensity of stream which became the surface stream after turning at the meniscus.

The energy spectrum of level fluctuation at narrow face shows that it comprises of the 'short period wave'. Its frequency is about,1 -2 Hz. Surface stream did not comprise of such peaks. The relationship between mould width and frequency of short period wave could be determined from experiments. It has been observed that short period waves come from harmonic oscillation of meniscus it can be considered that short period wave have little information about surface stream velocity. Correlation between level fluctuation [19] at narrow side and surface stream velocity can be given in terms of auto-correlation functions. The of level fluctuation at narrow face, X(t), and surface stream velocity ,V(t), can be calculated by using auto correlation function as follows:

$$\mathbf{ACF_{FF}(\tau) = S\, F(t).F(t+\tau)\, dt} \quad \textbf{(4)}$$

Where,

ACF_{FF} (τ : Auto correlation function

F(t) : A time domain data set among X(t) and V(t)

t : time

't : delaying time

The auto-correlation spectra in time domain help identification of long period waves. The mutual correlation function between level fluctuation at narrow side and surface stream velocity can be calculated using :

$$\mathbf{MCFxv(\tau) = SX(t).V(t + 't)\, dt} \quad (5)$$

Where,

MCF_{xv} (τ) : Mutual correlation function

X(t), V(t) : Two different time domain data

Fig.12 shows the enhanced downward jet angles produced by SENs with shortened bases and the resultant decrease in maximum wave heights. Wave height data reported from a pilot plant slab caster [10] show good agreement with the water model results for a full-base SEN. The slightly lower figures with liquid steel are expected; the mould studied by investigators was 100 mm thick, compared to the 60 mm thick water model mould, allowing the use of a somewhat larger bore SEN. The application of EMBR [8] significantly decreased the wave heights measured in liquid steel; the magnitude of the effect was similar to that achieved by SEN design modifications reported water model studies. In thin slab casting, the flow produced by a straight through SEN oscillated with a much lower frequency than that produced by a full-base SEN - 50 s compared to 5 s at 4 m/min casting speed. In the transition between a two jet full base SEN and a single jet straight through SEN, a range of mould flow patterns was observed that could be oscillatory or non-oscillatory, biased or symmetrical, or switching between patterns in an apparently random fashion.

In industrial terms, there are three main problems likely to be associated with the oscillatory flow phenomena during high-speed continuous Casting. These are essentially:

- The presence of surface waves indicates that there would be a non-uniform mould flux layer. The magnitude of wave height fluctuations in the thin slab water model was between 8 and 50 mm. Comparing these level variations to the available data that the index of both longitudinal cracks and inclusion spots are likely to be high in an operating thin slab caster, without appropriate counter measures.

- The oscillatory flow leads to high surface flow velocities, which are likely to cause entrapment of the mould flux. Peak surface stream velocities of around 1 m/s measured in the water model were high when compared to the findings of Kubota[7], who found that surface velocities should be kept in the range 0.15 and 0.25 m/s to minimise surface defects when casting low carbon steel.

- Increasing the magnitude and/or frequency of the surface wave oscillations observed in the water model, would increase the rate of change in mould level.

TECHNOLOGICAL ASPECTS OF THIN SLAB CASTER

Thin Slab Casting of Stainless Steels

Compact strip production (CSP), through thin slab casting process, developed by the SMS-Demag has been successfully applied to carbon steel and some stainless steel grades. However, due to problems in product quality, the wide scale application of the technology to a broad range of stainless and alloy steels has been lagged behind that of carbon steels. Recently, however, the thin slab casting of a variety of stainless and alloy steels has been proven at a pilot plant facility in Terni in Italy by a group of developers that included SMS-Demag, Accai Speciali Terni (AST), and Centro Sviluppo Materiali (CSM). Subsequent to the pilot facility, an industrial CSP plant for stainless steels was started in August 1, 2001 and in 2002 was in regular production with a product mix of 60% austenitic stainless steels, 27% ferritic stainless steels and 13% silicon steels, both grain oriented and non-grain oriented, at a production rate of 30000 ton per month. This machine is highly instrumented and includes automatic operation, a mould thermal monitoring system, an electromagnetic brake, liquid core reduction, dynamic soft reduction, and dynamic solidification control. Currently, strips produced by this machine has been applied to applications such as Bright Annealed AISI 304. This development allows thin slab casting technology and CSP technology in particular, to be applied to a wide range of stainless and high-alloyed steels[18].

Thermal Behaviour of the Mould

During operation, the mould distorts due to the steep thermal gradients. Although this distortion is very small, it may affect the size of the gap between the solidified shell and the mould, which, in turn, controls heat transfer. Thin slab moulds are expected to have higher heat flux and temperature owing to the higher casting speed. The accompanying thermal stress may cause permanent creep deformation near the meniscus, which affects mould life as well. Furthermore, maintaining a reliable, crack-free mould within close dimensional tolerances is also crucial to safety and productivity.

It has been reported that the heat flux in the lower part of the funnel-shaped mould varies markedly with time and is highly non-uniform across it, in contrast to moulds with parallel but narrowly spaced broad walls. It was suggested that the thermal behaviour of the funnel mould indicate a strong variation in contact between the strand and the mould, as the funnel disappears and the walls become flat. In contrast, compact strip-process moulds are straight along the casting direction, and the maximum mould protrusion at the meniscus is much larger.

Electro Magnetic Braking (EMBR)

A major advantage for the conventional slab casters has been steel quality, especially in terms of cleanliness and mould powder entrapment. However, this concern has been dramatically reduced for thin slab casters with the introduction of the ABB Electro Magnetic Brake (EMBR). The first EMBR test installation for thin slabs was made at Nucor Steel, Crawfordsville, IN. That equipment was later moved to Nucor Steel Berkeley, SC and subsequently, the second CSP strand installed in Berkeley was also equipped with EMBR. As the Berkeley plant uses an optical surface defect detection system after the hot rolling, it is an ideal installation for checking the effectiveness of the EMBR. Recent results show that with the EMBR, mould powder entrapment in hot rolled coil can be reduced by as much as 95 %, all the while casting at higher casting speeds. These quality improvements coupled with operating cost reductions, for example, increase of mould life; enables Nucor to compete more effectively with the conventional slab casters.. The result of the introduction of the EMBR to the thin slab casting process is that today, thin slab casters can compete very effectively with the conventional slab casters, particularly on quality levels.

In spite of the optimised mould and Submerged Entry Nozzle (SEN) geometry obtained by water modelling and computer simulations, the increase of the casting speed beyond 6 m/min leads to increasingly unstable flow conditions which might adversely influence the surface quality. By using the Electro Magnetic Brake (EMBR), the flow conditions in the mould can be controlled as a function of the casting width, the casting speed, the steel grade, the superheat and the SEN geometry. This means that by using an Electro Magnetic Brake, it is possible to achieve a good and reproducible surface quality within a wide range of casting speeds and steel grades while ensuring a high operational safety.

Thin slab casting imparts increased demands on the casting process. The casting speed compared to conventional slab casting is up to six times higher, which means meniscus turbulence increases leading to mould powder entrapment. Likewise, steel residence time in the old will become too short for separation of normal-sized inclusions and argon bubbles. The steel in thin slab casting is therefore always Catreated so that the inclusions coming with the steel do not clog the SEN but remain very small and thus harmless. Consequently, no clogging of the SEN occurs and thus argon use is not required. Further, the narrower the mould thickness, the greater will be the tendency for asymmetric steel flow, which leads to a wave generation at the mould narrow sides resulting in risk for mould powder entrapment. The EMBR results from thin slab casting shows the same beneficial effects as has been established for normal slab casting, but with the difference that the need for an EMBR is still further increased for thin slab casting. Thus, most of the new thin slab caster installations have included EMBR.

By using an EMBR, the steel flow speed is lowered and the "standing" wave close to the mould narrow side is reduced. As reported by Nucor Steel, Berkeley, casting at 5 m/min through a 4-port nozzle without EMBR produces a15 mm wave. With EMBR, the maximum wave is 4 mm.

CONCLUSION

In Indian steel plants, to facilitate high speed continuous casting of steel including casting of thin slabs, a well instrumented mould is a pre-requisite 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 break outs but also for ensuring surface quality. Redesign of the mould may also be necessary if sustained high speed 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 level fluctuation in a high-speed slab continuous caster mould leads to formation of surface defects and mould powder entrapment. The physical model flow dynamics studies (using water models) have identified that oscillation of flows and surface wave generation are the critical phenomena that occur under increased casting speed. The fluid flow in the high-speed slab mould is characterized by surface waves and the peak amplitude increases with increasing casting speed. Improvement in the SEN design and optimization of jet parameters is necessary to reduce the wave height The amplitude of the surface wave may be reduced by increasing the jet angle, thereby directing more of the flow down into the mould and strand. The amplitude of surface waves and the rate of change of amplitude, velocity of surface flows are likely to have a detrimental effect on mould lubrication, heat transfer uniformity and shell formation, as well as surface and internal quality through mould flux entrapment Therefore, appropriate remedial measures such as EMBR, SEN and mould design improvements need to be developed and optimised by Indian steel plants, It is also imperative to conduct full scale physical modelling experiments of various aspects of surface fluctuation and meniscus stability under different casting conditions to gain a fundamental understanding of these. phenomena. The technological challenges of high speed casting for the steel industry in India can be adequately addressed and surmounted, if there is a whole-hearted effort from academia, R&D organisation and steel industry to create a synergy and strategic alliance in this arena which requires multidisciplinary approach.

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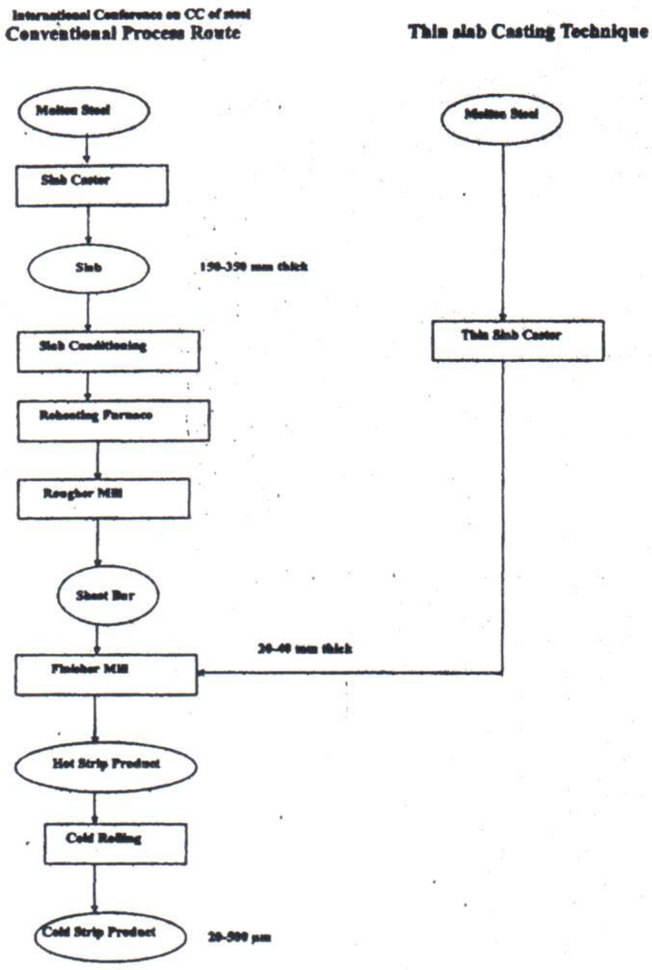

Figure 1. A Comparison between the process routes of Thin Slab and Conventional Casting Techniques

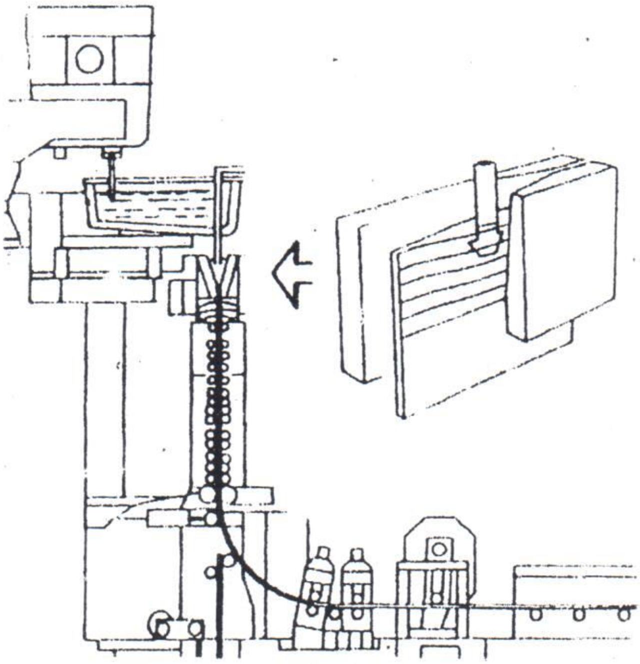

Fig. 2 : Schematic Diagram of A Typical Thin Slab Caster

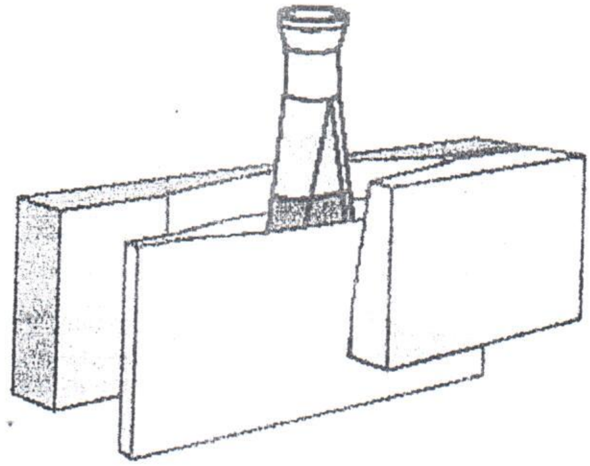

Fig. 3 : CSP Mould with Submerged Entry Nozzle

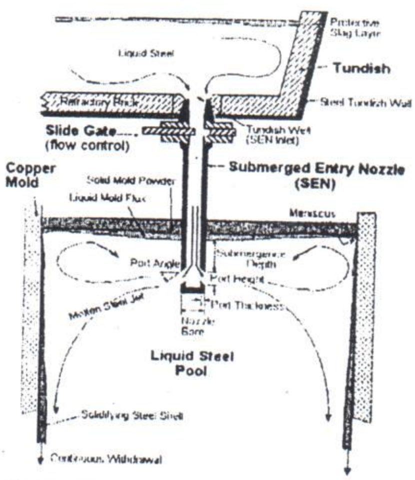

Fig. 4 : Schematic of tundish-mould operations

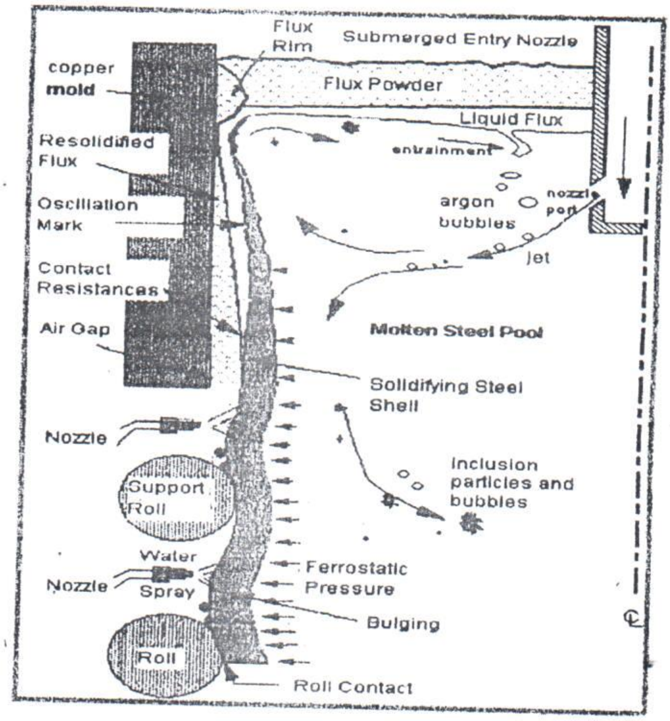

Fig. 5 : Mould and sub-mould processes

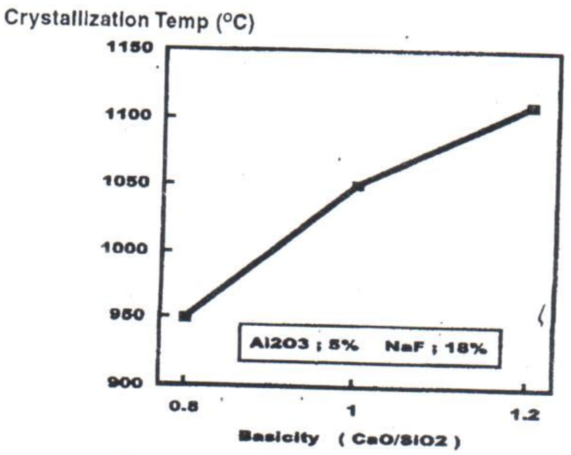

Fig. 6 : Influence of CaO/SiO2 on Crystallisation temperature.

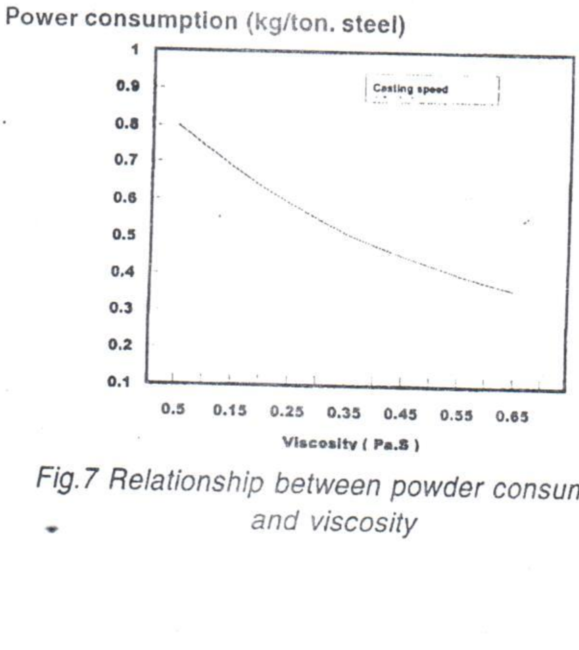

Fig.7 Relationship between powder consumption and viscosity

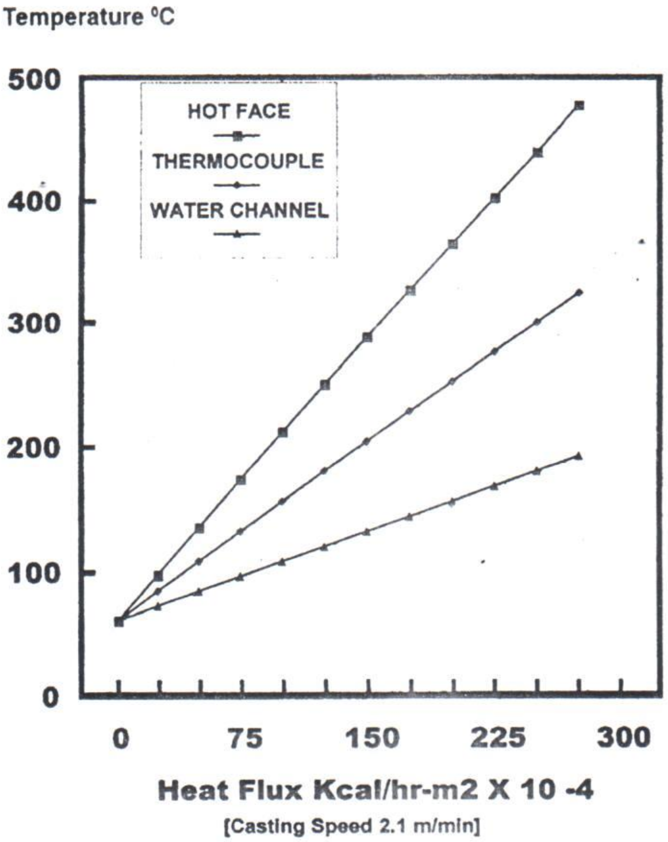

Fig. 8 : Measured and calculated temperature as a function of heat flux during high speed casting

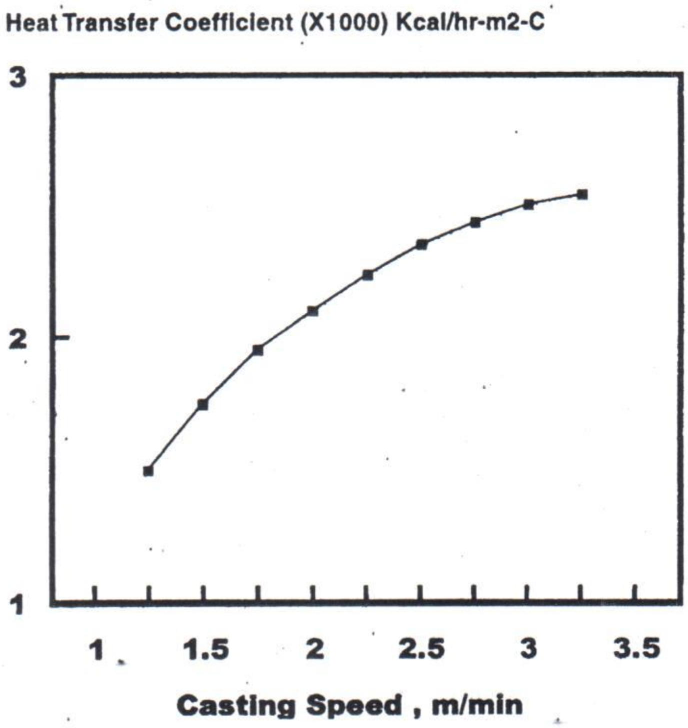

Fig. 9. Hot Face Maximum Heat Transfer Coefficient (Centreline) as a function of casting speed.

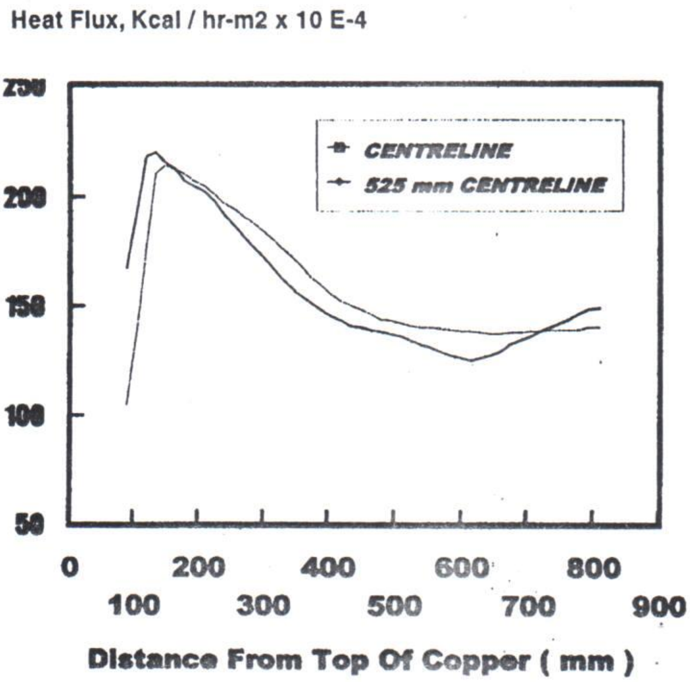

Fig. 10. Predicted heat flux for low carbon(<0.80%) steel with mould powder (E) and casting speed of 2.0 m/min

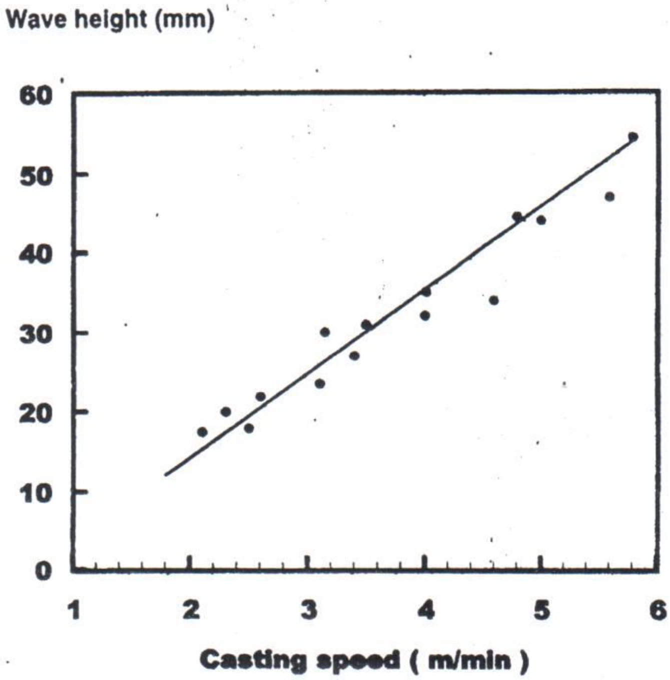

Fig. 11. Effect of casting speed on wave height for a standard SEN (Submerged Entry Nozzle)

Jet angle (Deg.)

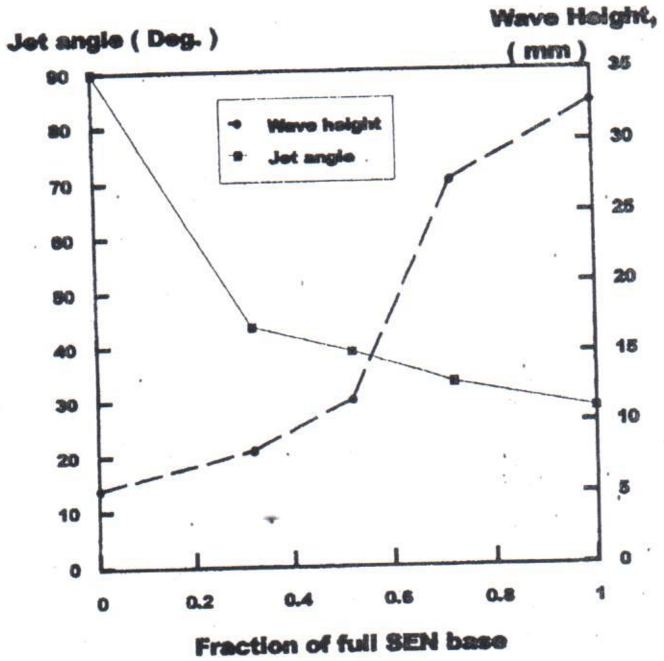

Fig. 12 : Variation in jet angle and wave height with SEN modification (250 mm wide SEN, Vc = 4m/min)