SUPPLEMENTARY TOOLS TO MEASURE AND UNDERSTAND THE FLOW IN THE CONTINUOUS CASTING MOULD

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For the production of clean steel it is important to control the flow in the mould. A lot of modelling work has already been done to study the flow behaviour in the mould. Measurements in the continuous casting mould are necessary to validate the modelling work, especially when multiphase flow is studied or when electromagnetic flow control systems are incorporated. For a few years, two measuring principles have been used to study the flow behaviour at the meniscus in the mould at Corus IJmuiden No.2 BOS. The main method is a simple flow measuring device, which consists of a refractory tube sealed at the bottom and fixed at a pivoting point at the top. The tube is submerged in the liquid steel in the mould. Measuring the resulting inclination angle reveals the flow direction and gives a measure of the velocity. In this way the effect of casting parameters on flow behaviour can be studied, such as the effect of the submersion depth of the SEN, the Ar-flow on the shrouding system (between the tundish and mould) and the change from double roll to single roll flow in the mould. Also, measurements are done with the 'nail board' method giving a snapshot of the flow direction at multiple locations in the meniscus. An electromagnetic sensor was used to measure the multiphase flow condition in the SEN. In this paper results of these measurements are shown and examples are compared with CFD calculations. A better understanding of the effect of casting parameters on the flow pattern in the mould was obtained using these supplementary tools.

KEYWORDS: continuous casting, mould, flow, measurement, sen, cfd simulation, corus ijmuiden

INTRODUCTION

It is well known that a stable casting practice is a requirement for the production of clean steel. One of the important factors is the control of the flow in the mould. Over the years, water modelling and numerical modelling have been used to study the flow behaviour in the mould.

In more recent work [1] modelling was combined with various measurements in the continuous casting mould in order to validate these results. This is necessary especially when multiphase flow is studied or when electromagnetic flow control systems are incorporated.

At Corus IJmuiden steel plant BOS No.2, two different tools have been used to study the flow behaviour at the meniscus in the mould. With the 'inclination angle' method the flow direction and the velocity can be measured for a certain period. When the 'nail board' method is applied a snapshot is obtained of the flow direction at multiple positions in the meniscus. In addition to this, experiments have been done with the 'Steel Flow Visualisation (SFV)' sensor. This electromagnetic device can be used to study the flow characteristics in the Submerged Entry Nozzle (SEN).

Although all these measurement methods, when used individually, will provide very useful information, it appeared that combining these methods generated additional results. Due to these supplementary tools a better understanding was obtained of the flow behaviour in the mould. In this paper a few examples are given of the flow behaviour in different casting situations. In one study, the experiments have been used to validate CFD calculations.

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	CC21 – before	CC21 – after	CC22
Machine	*curved*	*vertical bending*	*curved*
Slab thickness (mm)	225	225	225
Slab width range (mm)	950-1950	950-1950	950-2150
Electromagnetic flow control	*no*	*FCII*	*Ruler EMBr*
Range casting speeds (m/min)	1.0 - 2.0	1.0 - 2.2	1.0 - 2.0
Mould Length (mm)	900	900	900
Machine length (m)	38.4	39.7	35.1
Vertical Length (m)	-	2.5	-

▲ *Tab. 1*

Configuration of the slab casters of Corus Ymuiden BOS no.2.

Configurazione dell'impianto di colata Corus Ymuiden BOS no. 2

CASTER CONFIGURATION AT CORUS IJMUIDEN NO.2 BOS

No.2 steel plant at Corus Strip Products IJmuiden produces liquid steel via the BOF process at a level of approximately 7.3 million tons per year. Secondary metallurgy consists of two stirring stations, one RH-OB and one ladle furnace, with a heat size of 330 ton. The plant has two conventional two-strand casters CC21 and CC22, which have an annual capacity of about three million tonnes each. Further, the steel plant delivers liquid steel to the thin slab caster with in-line rolling of the 'Direct Sheet Plant', with a capacity of 1.3 million tons per year. Since the measurements, described in this paper, only apply to the two conventional casters, the thin slab caster is not considered here.

In 2006 the curved thick slab Caster CC21 was revamped into vertical with bending. The mould was equipped with an FCII type electromagnetic flow control system supplied by ABB. This enables the machine to cast at high throughputs, whilst maintaining a stable mould and meniscus flow. The level control is governed by a sliding gate on the tundish, moving in the thickness direction of the slab. Argon is injected to prevent clogging.

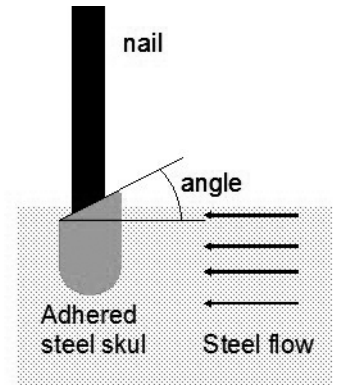
EXPERIMENTAL METHODS

In this section the measurement principles of the three used tools are described.

NAIL BOARD METHOD

The 'nail board' is a known method [1] to give an indication of the flow direction in the mould at the meniscus and a rough estimation of the flow speed. The flow direction can be obtained by analysing the position of the bow wave, which will be formed by the steel flow at the front of the immersed nail. Besides, a rough indication of the flow speed can be obtained from the angle of the adhered skull. After lifting out the nail both the position of the bow wave and the meniscus angle can easily be assessed by examining the adhered steel skull (see Fig. 1).

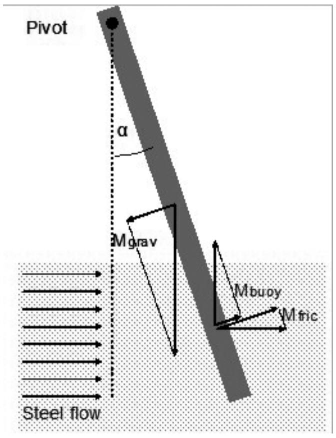
For the measurements in the mould, a stainless steel plate fitting in the mould is equipped with stainless steel nails with a diameter of 6 mm. The nails are distributed evenly over the length and width of the plate. This 'nail board' is immersed in the steel melt for about 6 sec. In this way a snapshot can be obtained of the flow direction at the meniscus at several positions.



▲ *Fig. 1*

Schematic view 'nail board' method.

Schema del metodo della "lavagna con puntine".



▲ *Fig. 2*

Schematic view 'inclination angle' method.

Schema del metodo dell' 'angolo di inclinazione'.

INCLINATION ANGLE MEASUREMENT

A suitable method to determine both the flow direction and the speed at the meniscus in the mould over a certain period of time is the 'inclination angle' measurement. When a tube is immersed in a steel melt, the steel will push the tube in the direction of the flow. When this tube is fixed at a pivot at the top, the resulting inclination angle (with vertical position) gives the direction of the flow and a measure of the flow speed (see Fig. 2). Only the velocity component perpendicular to the rotating axis of the tube can be measured.

The system used at Corus IJmuiden is shown in Fig. 3, and comprises a bearing (pivot) mounted at the front end of a beam and a tubular construction underneath, composed of a threaded end, a ceramic immersion tube with a closed end and a connection block in between. The immersion tube is a zirconia-graphite tube having a lifetime in the mould of 40-45 min, with an outer diameter of 23 mm and a length of 29 cm. The inclination angle is registered and logged continuously by a potentiometer (with low internal friction) located in the system beam. To protect the bearing and the potentiometer the beam is internally air cooled.

The 'inclination angle' is the result of the moment balance of the three acting forces:

- Gravity forces of all the components of the tube construction (i = threaded end, connection block, immersion tube):

$$M_{grav}=\Sigma_i(m_i\cdot l_i)\cdot g\cdot \sin(\alpha) \qquad (1)$$

- Buoyancy forces of the tube parts being immersed in the steel melt and in the slag layer:

$$M_{buoy}= \Sigma_{x=steel,slag}(V_x\cdot \rho_x\cdot l_x)\cdot g\cdot \sin(\alpha) \qquad (2)$$

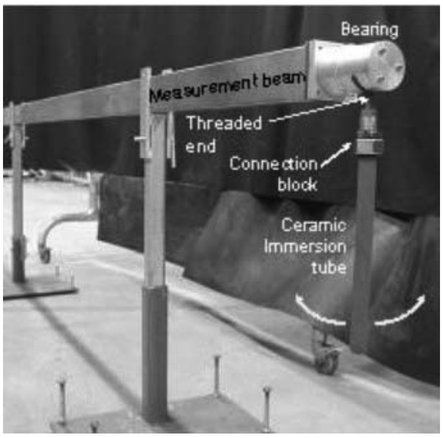
- Friction forces caused by the steel flow around the tube, being dependent on the flow velocity:

$$M_{fric}=0.5\cdot C_D\cdot A_{\perp,steel}\cdot \rho_{steel}\cdot v^2\cdot l_{steel}\cdot \cos(\alpha) \qquad (3)$$

In the equations (1) to (3), m = mass of the different components, l = arm of that component or immersed part, α = angle of inclination of the tube from its vertical position, V = volume of the immersed part of the tube, ρ = density of the liquid, C_D = drag coefficient, $A_{\perp,steel}$ = cross-sectional area of the immersed part of the tube and v = flow velocity.

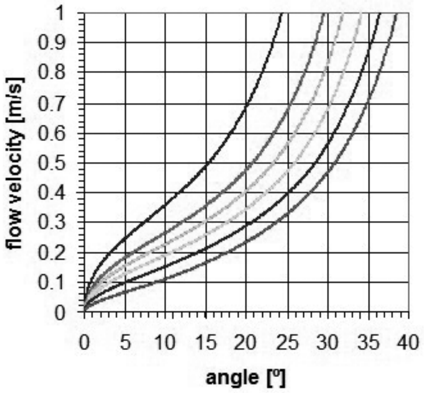
The flow velocity can be calculated from the moment balance $M_{grav} = M_{buoy} + M_{fric}$ and the measured angle.

In Fig. 4 the calculated flow velocity is given for different immersion depths as a function of the measured angle for a typical 'Inclination angle' system.



▲ Fig. 3 **Picture 'inclination angle' beam, with rotating ceramic immersion tube.**

Immagine del fascio dell' "angolo di inclinazione", con tubo in ceramica a rotazione e immerso.



▲ Fig. 4 **Calculated flow velocity as a function of the measured inclination angle for different immersion depths; for a typical 'inclination angle' configuration.**

Velocità di flusso calcolata in funzione dell'angolo di inclinazione misurato per diverse profondità di immersione, per una configurazione tipica di 'angolo di inclinazione'.

STEEL FLOW VISUALISATION

To obtain insight into the multiphase flow situation in the Submerged Entry Nozzle (SEN), the so called 'Steel Flow Visualisation (SFV)' sensor [2] can be used. This sensor is based on an electromagnetic sensing system, which measures the presence of metal in the SEN. The sensor was developed by Corus RD&T at Teesside Technology Centre (TTC) together with Lancaster University, University of Manchester and Metal Process Control (MPC). The sensor was tested in the heavy pilot plant at TTC and at several of the Corus casters.

In the final version of the sensor, the three transmitters and three receivers are placed in a non-magnetic stainless steel frame, which is constructed in the form an arc (see Fig. 5) and is positioned around the SEN; see Fig. 6.

The sensor cannot measure the flow of steel as such, but is capable of detecting the amount of steel in the field of measurement. In this way, an indication is obtained of the gas fraction in the liquid steel in the SEN and by studying how the steel volume changes it is possible to deduce changes in the flow pattern.

EFFECT OF ARGON FLOW RATE ON THE FLOW IN THE MOULD

It is generally accepted that the argon injected into the feeding system from the tundish to the mould can lead to undesired effects in the mould, such as bubble or mould powder entrapment. Also, the flow characteristics and the stability of the flow

Fig. 5

Picture of the 'Steel Flow Visualisation' sensor showing the transmitters and sensors.
Immagine del sensore di "Visualizzazione del flusso di acciaio", che mostra sensori e trasmettitori.

Fig. 6

Picture of the SFV sensor in position around the SEN.
Immagine del sensore SFV in posizione intorno al SEN.

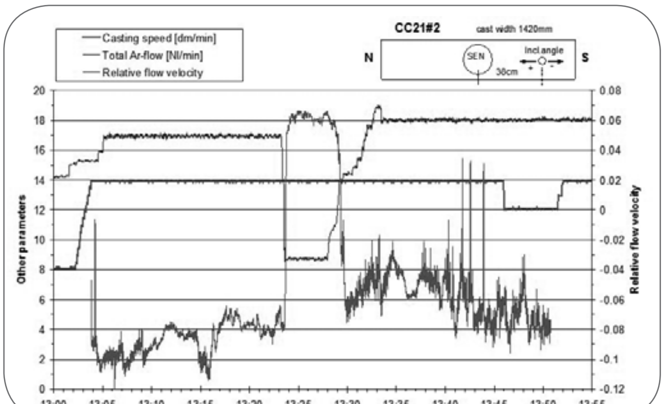


Fig. 7

Evolution of casting parameters, with effect of Ar-flow on the measured meniscus flow direction and velocity.
Andamento dei parametri di fusione, con effetto del flusso di Ar sulla direzione e la velocità misurata di flusso al menisco.

pattern in the mould are influenced by the flow characteristics in the feeding system [3].

The effect of the Ar-flow in the feeding system on the flow in the mould was measured in the mould using the 'inclination angle' method.

At rather high Ar-flows of 17-18 Nl/min a 'reversed' flow pattern is present in the mould with the measured flow at the meniscus being directed towards the narrow face, see Fig. 7. After decreasing the Ar flow to 9 Nl/min, a clear change of the flow pattern was found to a 'normal' flow pattern with a flow at the meniscus being directed towards the SEN. When the Ar-flow was changed back again to its higher value, the flow pattern changed back to a 'reversed' pattern with a flow at the meniscus directed towards the narrow face.

When using an Ar-flow in between these values, it appears that a non-stable flow situation is obtained in the mould, see Fig. 8. At an Ar-flow of 13 Nl/min the direction of the flow at the meniscus is fluctuating between directed towards the narrow face and towards the SEN without further deliberate changing of the casting parameters.

This effect of the Ar-flow on the flow pattern in the mould can be caused by the lifting effect of the Ar-bubbles in the mould, by a changed multiphase flow characteristic in the feeding system or by a combination of both.

The argon injected into the feeding system is generally considered to behave as a dispersed multiphase flow. However, it is also known that a dispersed flow can change to an annular type of flow when sufficiently high gas fractions are applied.

In previous work done by van Oord [4], the transition of the flow characteristics in the SEN was studied. From theoretical considerations describing the pressure development in the feeding system it was found that gas fractions may rise locally, especially near the sliding gate, in such a way that the flow pattern changes from dispersed flow to an annular flow. This phenomenon is not only affected by the gas feeding rate, but also the sliding gate position and the difference between steel height in the tundish and steel height in the mould. Water modelling and additional CFD calculations supported these assumptions.

This was further confirmed by a plant trial investigating

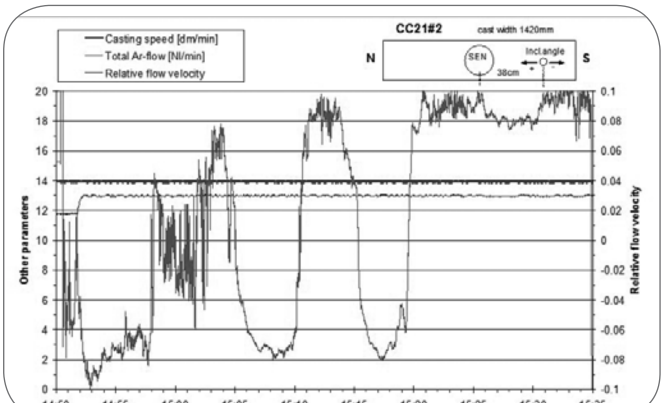


Fig. 8

Evolution of casting parameters, with effect of Ar-flow on the measured meniscus flow direction and velocity.
Andamento dei parametri di fusione, con effetto del flusso di Ar sulla direzione e la velocità misurata di flusso al menisco.

the effect of the Ar-flow on the flow condition in the SEN, using the SFV-sensor at CC22 (see Fig. 9).

The SFV-signal shows two distinct modes. The somewhat stable and high sensor signal is explained as a full bore with dispersed argon bubbles. The more unstable and lower signal was found to describe a separated flow with a steel stream within or around a continuous argon phase. A clear correlation was found between this SFV-signal and the argon flow rate. The transition from the one characteristic to the other occurs when the argon flow rate passes 13 Nl/min for the casting conditions applied.

In other trials using the SFV it was found that this transition occurs at a much higher argon flow rate when casting at a higher throughput.

The combination of the results of the 'Inclination angle' and SFV trials shows that the flow pattern in the mould may well be affected by the flow situation in the feeding system.

EFFECT OF IMMERSION DEPTH SEN AND FCII ON FLOW PATTERN IN THE MOULD

During the revamping of Corus IJmuiden CC21 to a vertical with bending caster, the mould was equipped with a FCII type electromagnetic flow control device of ABB. This device has one magnetic pole below and one above the exit ports of the SEN, to avoid deep penetration of the steel jet from the SEN into the strand and to stabilize the flow near the meniscus to avoid slag entrainment. Numerical modelling [5] has been used to determine how to operate this device effectively and to obtain the correct input parameters for the optimal flow control. After the start up of the caster, flow measurements were done in the mould to further tune the FCII settings in the casting practice and to validate the numerical modelling. Below a few examples of both measured and calculated flow profiles are given.

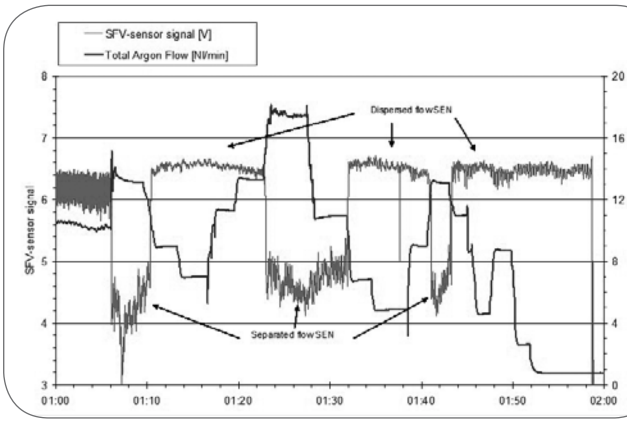
To predict the flow situation in the mould, the numerical model described by Bal [5] at the EPM2006 conference has been used. Calculations have been done with this model in the ANSYS-CFX10 environment, using the 'magneto-hydrodynamics (MHD)' model, the turbulence damping model and the full multiphase model using a single bubble size of 0.5 mm.

The strong influence of the FCII on the flow behaviour in the mould is illustrated in the examples shown in Fig. 10. In this example a 'normal double roll' flow pattern with rather high velocities at the meniscus is found when the FCII is not used. When the FCII is used, the flow pattern changes to reversed. At the meniscus this pattern leads to a split flow pattern. In one part of the meniscus this flow is directed towards the SEN, whilst in the other part the flow is directed towards the narrow side. This is caused by the jet exiting the SEN rising to the surface and impinging the meniscus somewhere halfway between the SEN and the narrow face. The observed meniscus velocities are lower when compared to the case without FC-II.

The main focus of the flow measurements was to investigate the effect of the FCII settings on the flow pattern in the mould and its stability when changing the immersion depth of the SEN. The immersion depth is changed to minimise erosion of the SEN at the meniscus level.

When flow measurements are done in the flow situation as shown in Fig. 10 at the right hand side, it might well be possible that the 'inclination angle' tube is immersed in the area in which the flow impinges the meniscus area and separates into the two horizontal flow directions. To detect this, the tube is manually moved during the measurement, to see whether another flow field is present near the tube.

The 'Inclination angle' measurements showed a 'reversed' flow when the FCII was used and the SEN was immersed deeply into the mould. This can be seen in Fig. 11 (periods 13:30-13:42, 14:28-14:40), in which at high immersion depths of the SEN, the measured flow direction appears dependent on the direction in which the immersion tube is manually moved. This points to a flow situation at both sides of the SEN, in which the meniscus flow direction is



▲
Fig. 9

Evolution of casting parameters CC22, with the effect of Ar-flow rate on SFV-sensor signal using a casting speed of 1.2 m/min at a cast width of 1600 mm.

Evoluzione dei parametri di colata CC22, con effetto della velocità del flusso di Ar sul segnale del sensore SFV utilizzando una velocità di colata di 1,2 m / min a una larghezza di colata di 1600 millimetri.

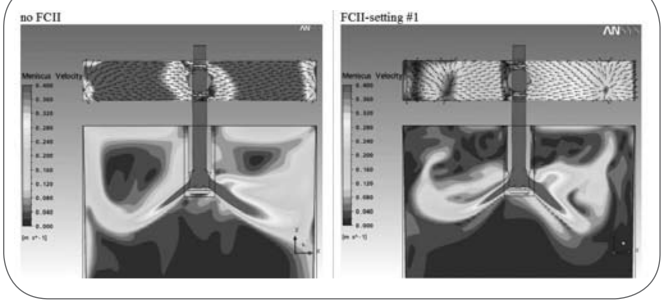


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Fig. 10

Calculated effect of the FCII on the flow direction at the meniscus in the mould, from numerical modelling at high immersion depths of the SEN: left) no FCII and right) FCII-setting #1. The colour scale at the left of both graphs applies only to the meniscus area shown at the top.

Effetto calcolato della FCII sulla direzione di flusso al menisco nella lingotiera, dalla modellazione numerica ad alta profondità di immersione del SEN: sinistra) nessun FCII e destra) impostazione FCII # 1. La scala di colore alla sinistra di entrambi i grafici si riferisce solo all'area del menisco mostrato in alto.

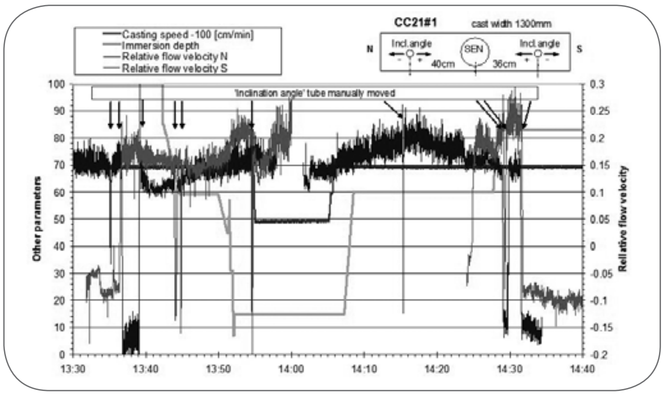

Fig. 11

Evolution of casting parameters CC21#1, with effect' immersion depth SEN' on the flow velocity measured with the 'Inclination angle' method; using FCII-setting #2, a typical Ar-flow and casting width 1300 mm.

Evoluzione dei parametri di colata CC21 # 1, con effetto 'profondità di immersione SEN' sulla velocità di flusso misurata con il metodo dell' 'Angolo di inclinazione'; utilizzando l'impostazione FCII # 2, un flusso tipico di Ar e larghezza di colata di 1300 millimetri.

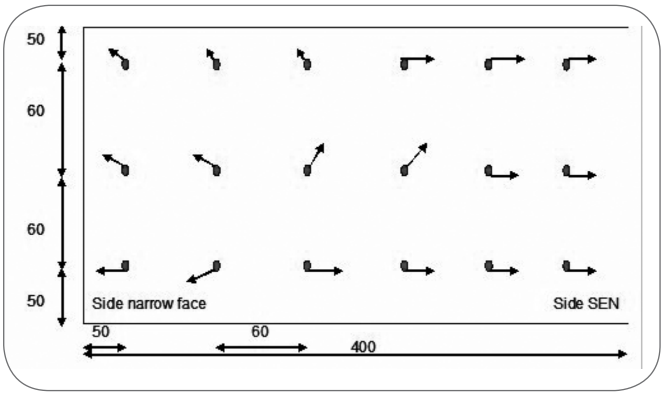

Fig. 12

Flow directions CC21#1 N-side from 'nail board' with FCII-setting#2, deeply immersed SEN, typical Ar-flow, v cast=1.7 m/min, cast width of 1300 mm.

Direzioni di flusso CC21 # 1 lato N da 'lavagna a puntine' con impostazioni FCII # 2, SEN immerso in profondità, flusso tipico di Ar, velocità di colata = 1,7 m / min, e larghezza di 1300 millimetri.

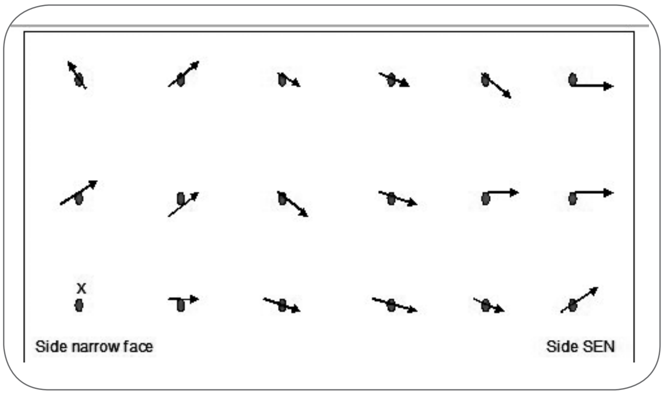

Fig. 13

Flow directions CC21#1 N-side from 'nail board' with FCII-setting #3, small immersion depth SEN, typical Ar-flow, v cast=1.7 m/min, cast width of 1300 mm.

Direzioni di flusso CC21 # 1 lato N da 'lavagna a puntine' con impostazioni FCII # 3, bassa profondità di immersione SEN, flusso di Ar tipico, velocità di colata = 1,7 m / min, e larghezza di 1300 millimetri.

seen to be directed both towards the SEN and towards the narrow face.

This observation was confirmed by the 'nail board' measurement (see Fig. 12) showing a flow pattern at the meniscus directed towards SEN (near the SEN) and to the narrow face (near the narrow face). The transition between both flows is about halfway, which is more or less the location of the immersed tube of the 'inclination angle' method.

Consequently, when the 'inclination angle' tube is manually moved to one of both sides, the tube will change from the one to the other flow field and remain at that direction. When the tube was only moved to the vertical position (see Fig. 11 at approx. 13:35), it didn't enter the other flow field and the tube came back into its previous position.

At small immersion depths of the SEN and using the FCII, both the 'inclination angle' measurement (see Fig. 11) and the 'nail board' (see Fig. 13) show a 'normal' double roll flow, with flow at the meniscus being directed towards the SEN.

Numerical modelling has been used to explain these observations; see Fig. 14. When the SEN is immersed deeply in the mould, the exit port is just above the lower magnetic pole. The main flow out of the exit ports will enter this electromagnetic affected zone and will either slow down or be reflected. Together with the lifting effect of the argon, this will result in upward bending of the main flow direction before it reaches the narrow face (see also right hand side image of Fig. 10, right hand side of left image of Fig. 14).

When the immersion depth of the SEN is small, the exit ports of the SEN are well above this magnetic pole. Consequently the main flow will not directly enter the electromagnetic affected zone and flows above this area towards the narrow face. Here it will separate into a downward and upward flow along the narrow face. This upward flow will enter the meniscus area near the narrow face and will cause a meniscus flow directed towards the SEN.

By combining measurements and modelling, the numerical model has been validated and a better understanding of the effect of the FCII on the flow in the mould has been obtained. These combined results are used to obtain the optimal settings of the FCII for the different casting situations.

CONCLUSIONS

Both the 'inclination angle' and 'nail board' method are useful tools to generate information on the flow behaviour at the meniscus in the mould. The combination of these tools will give a better insight into the flow pattern, especially at situations in which different flow directions are present at one side of the strand and in situations where the flow pattern changes.

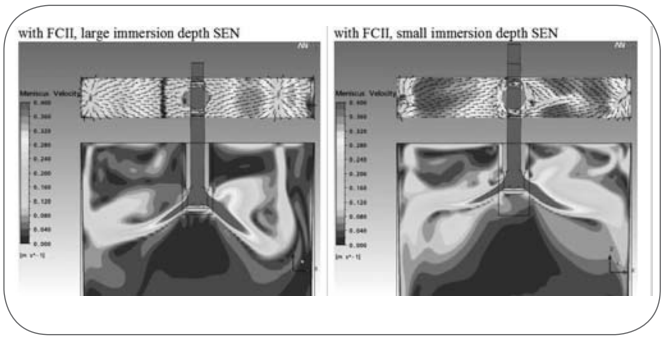

Fig. 14

Calculated effect of the immersion depth of the SEN on the flow in the mould and flow directions at the meniscus with FCII-setting #2: left) high immersion depth SEN and right) small immersion depth SEN. The colour scale at the left of both graphs applies only to the meniscus area shown at the top.

Effetto calcolato della profondità di immersione SEN sul flusso nella lingottiera e direzioni del flusso al menisco con impostazione del FCII # 2: sinistra) ad alta profondità di immersione del SEN e destra) a bassa profondità di immersione del SEN. La scala di colore a sinistra di entrambi i grafici si applica solo alla zona del menisco mostrato in alto.

CFD calculations describing the flow pattern in the mould correspond well with the measured results and are helpful to understand the measured flow behaviour.

A better insight was obtained into the effect of the argon flow rate on the flow behaviour in the mould and how this can be affected by the flow characteristic in the SEN, by using the ‘inclination angle’ method and ‘Steel Flow Visualisation’ measurements.

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REFERENCES

1] B.G. Thomas, Q. Yuan, S. Sivaramakrishnan, T. Shi, S.P. Vanka, M.B. Assar, ISIJ International, Vol.41 (2001), No.10, p.1262-1271

2]S.R. Higson, P. Drake, A. Lyons, A. Peyton, B. Lionheart, Proc. 5th European Conference on Continuous Casting, June 20-22, 2005, Nice, France, p.468-474

3] S. Kunstreich, P.H. Dauby, Proc. 4th European Conference on Continuous Casting, October 14-16, 2002, Birmingham, UK, p.489-499

4] J. Van Oord, T.W.J. Peeters, A.E. Westendorp, S.R. Higson, J.P.T.M. Brockhoff, Proc. SteelSim Conference, September 12-14 2007, Graz, Austria, p.179-184..

5] D. Bal, J.P.T.M. Brockhoff, W.F.M. Damen, T.W.J. Peeters, Proc. 5th Int. Symp. Electromagnetic Processing

ABSTRACT

STRUMENTI SUPPLEMENTARI PER LA MISURAZIONE E LA COMPRENSIONE DEL FLUSSO NELLA LINGOTTIERA DI COLATA CONTINUA

Keywords: colata continua, produzione

Nella produzione di clean steel è importante controllare il flusso nella lingottiera. Già molti studi di modellazione sono stati eseguiti per analizzare il comportamento del flusso nella lingottiera. Per validare gli studi di modellizzazione è necessario effettuare misurazioni all’interno della lingottiera di colata continua, in particolare quando si studia il flusso multifase o quando sono incorporati i sistemi di controllo di flusso elettromagnetici.

Per alcuni anni, presso lo stabilimento Corus IJmuiden No.2 BOS, sono stati utilizzati due principi di misurazione nella lingottiera per studiare il comportamento del flusso al menisco. Il metodo principale è costituito da un semplice dispositivo di misurazione del flusso, che consiste in un tubo refrattari saldato al fondo e fissato in alto ad un punto di snodo. Il tubo è immerso nell’ acciaio allo stato liquido, nella lingottiera. Attraverso la misurazione dell’ inclinazione conseguente è possibile stabilire la direzione del flusso ed avere una misura della velocità. In questo modo è possibile studiare l’effetto di alcuni parametri di colata sul comportamento del flusso, come ad esempio l’effetto della profondità di immersione del SEN, il flusso di Ar sul sistema (tra tundish e lingottiera) e il cambiamento da double roll a single roll flow nella lingottiera. Inoltre, le misurazioni vengono effettuate con il metodo della “lavagna con puntine’ che fornisce un quadro della direzione del flusso in più punti del menisco. Per misurare il flusso multifase in condizione SEN, è stato utilizzato un sensore elettromagnetico.

In questo documento vengono presentati i risultati di queste misurazioni e alcuni esempi vengono confrontati con i calcoli CFD. Utilizzando questi strumenti supplementari si è ottenuta una migliore comprensione degli effetti dei parametri di colata sul flusso nella lingottiera.