HOW TO IMPROVE STEEL CLEANLINESS IN CC MOULD ? - ARCELOR RESEARCH PAST EXPERIENCE AND NEW RECENT DEVELOPMENTS[1]

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Abstract

The inclusions elimination is getting more and more important to obtain clean steel, particularly in continuous casting mould, which is the last reactor where steel remains liquid. A modelling tool for predicting what happens in the caster is still a real challenge, because of the large number of phases present in the steelmaking process : liquid steel, slag layer, gas bubbles and inclusions (with a large range of composition and rheology). Phenomena occurring in the CC mould are therefore quite complex and a good description is the key factor for a reliable prediction of the steel cleanliness in mould and thus of the quality of the final products. The hydrodynamics in mould, depending on the process parameters such as the casting velocity, the argon flow rate, the mould dimensions, the nozzle design, the SEN immersion depth, can be represented by the liquid steel flow and its turbulence. These parameters directly control the inclusions behaviour in the liquid steel in the mould. Water model, mercury model and also industrial trials are investigated by some special measurements devices (Particle Image Velocimetry, Sub-meniscus Velocity Control sensor…) and by numerical simulation. This paper aims at presenting these different experimental and numerical tools, developed and used in Arcelor Research. It shows it is possible to modify flow patterns inside the mold, acting on process parameters as by taking profit of some electromagnetic (EM) actuators. Inclusions behaviour (alumina and slag) can then be positively controlled and their entrapment by the slag solidifying shell limited.

Key words: Continuous casting mould; CFD; Water model experiments

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1 INTRODUCTION

Development of the continuous casting technology is driven by the ever increasing demand of production volume and with particularly cleaner quality. To ensure this demand, Arcelor-Mittal has performed in the past and performs today modeling of the continuous casting process. This paper aims at showing the Arcelor-Mittal experience concerning the hydrodynamics developing in the CC mould. It is divided into three main parts. The first part highlights the laboratory pilots (water and mercury experiments) and industrial trials (velocity measurement and inclusions detection system). The second part deals with the numerical modeling of the process, with a special attention paid to the validation of the model. The last part presents the numerical modeling results concerning various process parameters influence and the impact of an electromagnetic actuator in the mould.

2 LABORATORY AND INDUSTRIAL EXPERIMENTS

2.2 Water Experiments

Flow visualizations and velocity measurements are made using a half scale Plexiglas water model of the nozzle and mould (Figure 1).

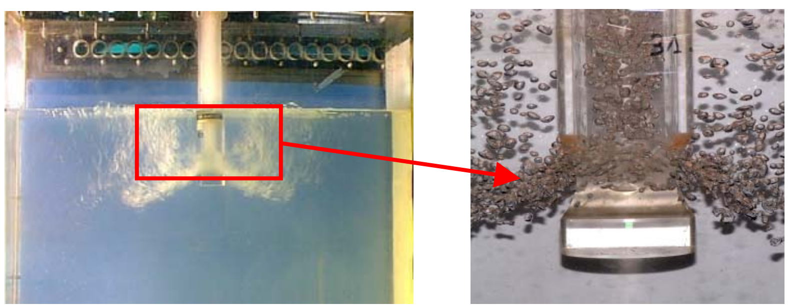


Figure 1 : Illustration of the pilot used for understanding and numerical tool validation

Hydrodynamics parameters such as instantaneous velocity are measured with a Laser Doppler Anemometer (LDA) at different positions in the mould, while the flow pattern is instantaneously determined with a Particle Image Velocimeter (PIV). The slag behaviour can be experimentally reproduced by adding an oil layer at the surface of the mould. In this case, qualitative results can be obtained thanks to recording with a high speed video camera and analyzed by appropriate image treatment
The water experiment allows us to visualize the flow phenomena developing in the mold and is often used for steel applications (see for example the papers of *Yamahita & Igichu*, 2001 or *Kwon et al.*, 2006) since measurements in liquid steel is still a challenge (harsh environment: high temperatures and opaqueness). Moreover, water pilot is a useful tool to validate the numerical modelling (see paragraph 3.2).

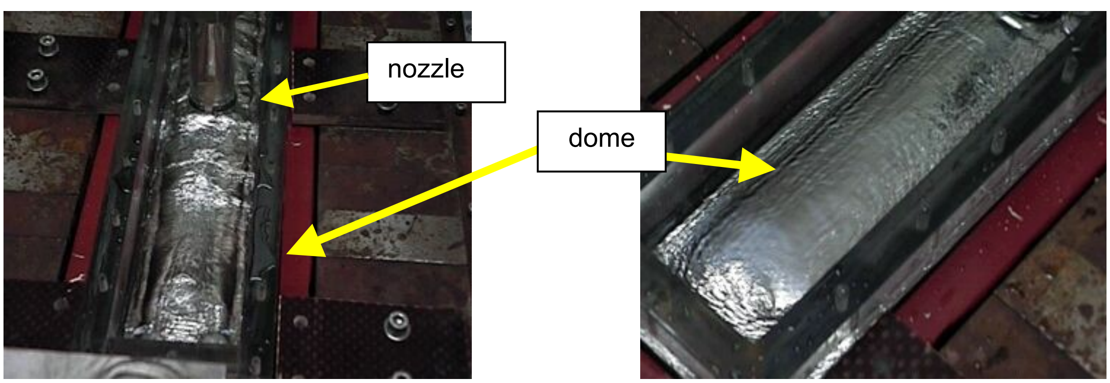
2.2 Mercury Model

Mercury model is, like the water model, a useful research tool and particularly to have a better understanding of the physical mechanisms acting on the flow stability and to

perform an initial design and adjustment of the actuators before industrial implementation.
Liquid steel is an electrical conductive medium and can be easily submitted to Joule heating or Lorentz forces. Roughly speaking, we can distinguish 3 main types of electromagnetic systems for liquid steel:

- High frequency (frequency higher that 1 kHz) for creating a repulsive force on the liquid steel in the top region of the continuous casting mould, for instance for the improvement of the lubrication by an increase of the gap between mould and solidifying shell
- low frequency AC field (less than 5 Hz); electromagnetic skin depth is then higher that several centimetres and efficient stirring can be performed in the liquid steel reactor (ladle or mould)
- DC field system; this system is mainly used for braking purpose in continuous casting mould and decrease agitation in the top region of the mould.

Arcelor-Mittal built in collaboration with EPM-Madylam laboratory a mercury CC mould model. Geometrical scale was 1/3. Main hydrodynamic similarity criteria (Froude, Reynolds, Weber) are correctly respected, as well as specific criteria for electromagnetic mechanisms.
Figure 2a shows some results about the AC field imposition (1500 Hz) in the top region of the mould: a dome shape is obtained and this will improve the lubrication and will help to suppress the solidified hooks, which are known to easily entrapped inclusions. AC field creates some stirring movement, which destabilises free surface and damages initial solidification. Figure 2b corresponds to a superimposition of a DC field localised at the free surface: an important damping of the free surface oscillation is observed but the dome shape remains.



(a) (b)

Figure 2 : Meniscus shape in mercury model: (a) AC field only - (b) AC+DC field superimposition

2.3 Industrial Trials

- *Velocity measurement at meniscus*

The Sub-meniscus Velocity Control (SVC) has been developed to characterize the impact of the ElectroMagnetic brake, tested in Sollac Dunkerque from 1991 to1994, on the hydrodynamics in the CC mould. The system (Figure 3) consists of a Cermotherm tube which is immersed in the liquid steel in the CC mould at the meniscus. The torque

exerted by the fluid on the tube is measured thanks to a torque gauge. The knowledge of the torque leads to the calculation of the liquid metal velocity.
This system is presently used in Arcelor-Mittal plants to investigate modifications of the CC process (new SEN design, argon/metal ratio, actuators,…) and to try to qualify the products quality at the level of the slab. It is moreover useful to validate the numerical modelling performed for industrial configurations (see paragraph 3.3).

- *Steel cleanliness characterization – Inclusions detection*

The technique used is optical counting and recognition system of the defects on strip: Automatic Surface Inspection System (ASIS). The technique consists in lighting the strip surface, recording images with a high speed CCD camera (Figure 4) and then processing the images by image analysis software (*P. Rocabois et al.*, 2002). Both surfaces are inspected. A first selection is done and then the software only treats the images concerning the part of the strip affected by defects in order to recognize the different defects. The first selection is based on gray level analysis. The identification of defects is based on comparison with images of a database (shape and gray level).

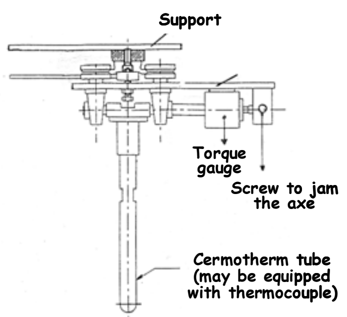


Figure 3 : A schematic of the SVC system

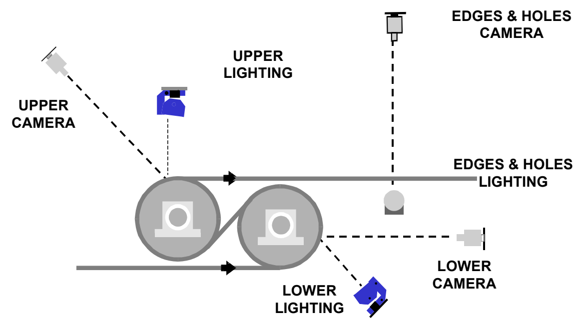


Figure 4 : A schematic of the ASIS system.

The defects are classified according to their size and position in the width of the strip (Figure 5 and Figure 6). Slivers originating from mould slag are observed to be concentrated mainly in the centre of the slab width for a 1240-1290 mm slab with a possible asymmetric distribution on some coils as shown on Figure 5 (the sliver indexes given hereafter are relative sliver indexes specific to each figure). The distribution of inclusion lines originating from alumina clusters is observed to be rather uniform (Figure 6).

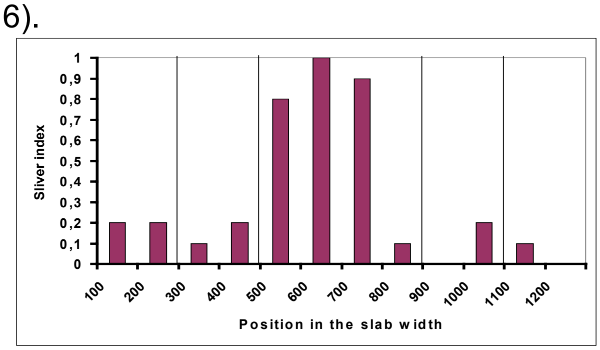


Figure 5 : Distribution of mold slag slivers as observed on IF-Ti steel grades. Slab width: 1240 and 1290 mm

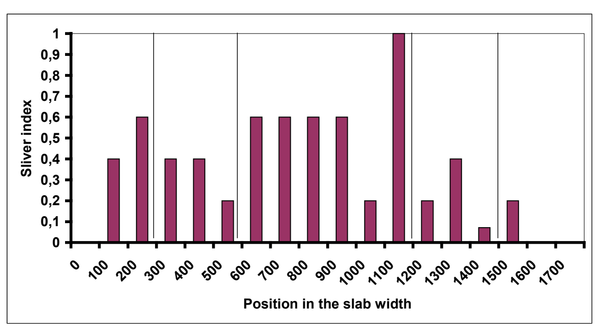


Figure 6 : Distribution of inclusion lines whose origin is alumina clusters as observed on IF-Ti steel grades. Large slab width: 1700-1800 mm.

3 NUMERICAL TOOL

The numerical tool used for calculations of gas/liquid steel two-phase flows and inclusions trajectories in the continuous casting machine is presented hereafter. Numerous literature papers are still published (see for example *Zhang et al.*, 2006 or *Thomas*, 2006) on numerical modelling of CC mould since this approach allows a good understanding of fluid phenomena.

3.1 Description of the Mathematical Approach

This numerical tool (*Domgin et al.,* 2002-2005) can simulate flow, temperature and inclusions behaviour in the continuous casting machine. It takes into account the effect of the sealing argon flow rate coming from the SEN and the possible effect due to electromagnetic fields (*Gardin et al.*, 1994 and *Galpin et al.,* 2002).

Currently, the commercial finite volume code Fluent is used for the numerical calculations. The Lagrangian approach (*Kubo et al.*, 2002) is chosen for the discrete phase description: the fluid phase is treated as a continuum by solving the time-averaged Navier Stokes equations while the bubbles trajectories are computed individually at specified intervals during the fluid phase calculation, and can exchange momentum with the carrier phase (two-way coupling). The most significant forces acting on bubbles (drag, buoyancy, added mass and pressure gradient) are taken into account. Turbulent predictions for the continuous phase are computed with the Fluent specific realizable (K-ε) model (*Fluent*, 2002) and the additional production of turbulence due to bubbles (*Boisson and Malin* (1996)) has also been implemented in Fluent software both in K and ε equations, taking into account the production of turbulent kinetic energy due to drag forces (*Domgin and Gardin* (2001)).

In our simulations, the inclusion behaviour (alumina and slag inclusions) is simulated with a Lagrangian approach and a one-way coupling is chosen (no direct impact on the liquid steel flow).

For EM applications, a special coupling has been implemented between Fluent and Flux©. An electromagnetic force $\vec{\mathrm{F}}_{\mathrm{em}}$, calculated thanks to the commercial software Flux©, is added in the momentum conservation equation. The magnetic flux $\vec{B}$ is obtained by solving Maxwell equations. The knowledge of $\vec{B}$ leads to the additional term $\vec{\mathrm{F}}_{\mathrm{em}}$ (Lorentz force) from equation below:

$$\vec{F}_{em} = \vec{J} \wedge \vec{B}$$

Where $\vec{J}$, the current density is deduced from:

$$\vec{J} = \sigma\left[\vec{E} + \vec{U} \wedge \vec{B}\right]$$

$\vec{E}$ is the electrical field and σ is the electrical conductivity. The coupling considers consequently the sum of the temporal evolution of the magnetic field and of the influence of the fluid velocity field on the magnetic force. This last contribution is calculated thanks to User Defined Functions directly implemented in Fluent. This coupling allows us to study EM actuators influence on CC mold hydrodynamics. Examples of such results will be showed in the paragraph 4.3.

3.2 Application and Validation for the Water Model Configuration

We compare in the Figure 7 and Figure 8 the numerical results obtained in the water model configuration with the experimental ones for both instantaneous horizontal velocity just below the free surface and velocity magnitude along the narrow face. These comparisons reveal globally good agreement. Moreover, a spectrum analysis of this signal reveals a very good prediction of the numerical approach for the low frequencies flow oscillation.

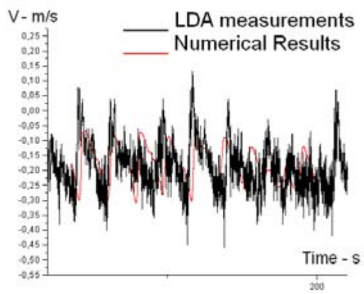


Figure 7 : Instantaneous horizontal velocity below the meniscus - Good agreement between LDA measurements and CFD calculations

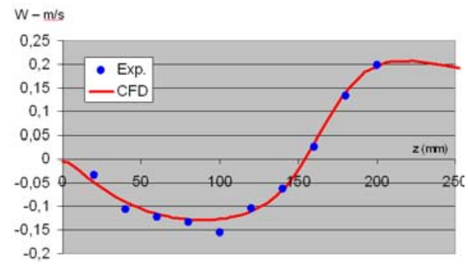


Figure 8 : Mean velocity magnitude along the narrow face - Good agreement between LDA measurement and CFD calculations

This experimental approach on water model confirms the unsteady behaviour of the flow in the mould (horizontal velocity fluctuations between -0.4 m/s and +0.15 m/s) and allows to validate the numerical tool developed for these configurations.
The Volume Of Fluid (VOF) model, used to simulate the interface deformation between different phases, has been qualitatively validated by comparison with an oil/water pilot experiment (Figure 9). The pictures show a good agreement in terms of visual interface deformation but improvements in the model have still to be brought to obtain quantitative agreements between LDA measurements and numerical simulation.

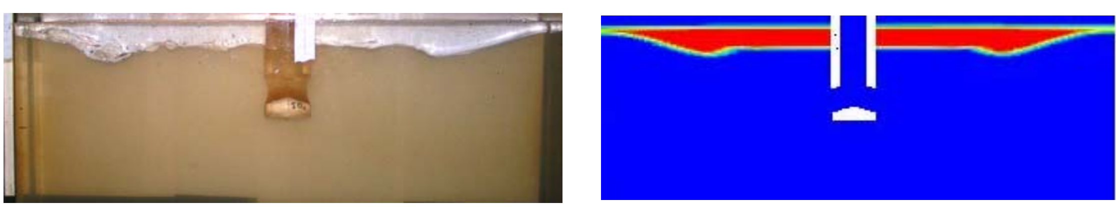


Figure 9 : Good agreement between experimental and VOF model - Oil/water interface deformation

3.3 Application and Validation on Industrial Configuration

- *Velocity measurement*

An example of velocity measurement at meniscus according to process parameters variation is illustrated on Figure 10. Velocity fluctuations are observed mainly associated with process parameters variation during the casting.

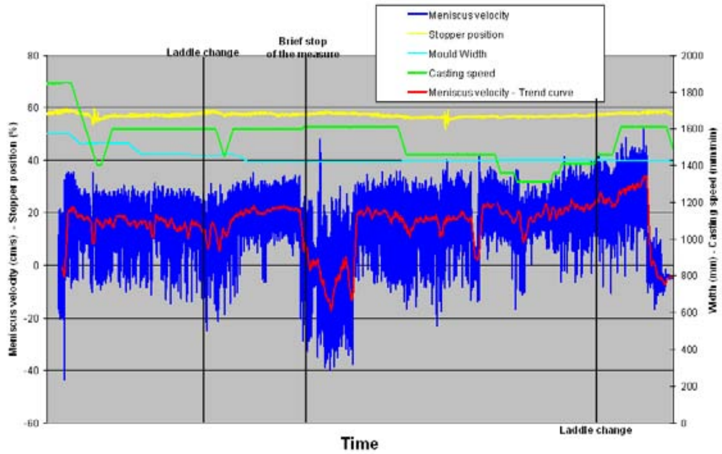
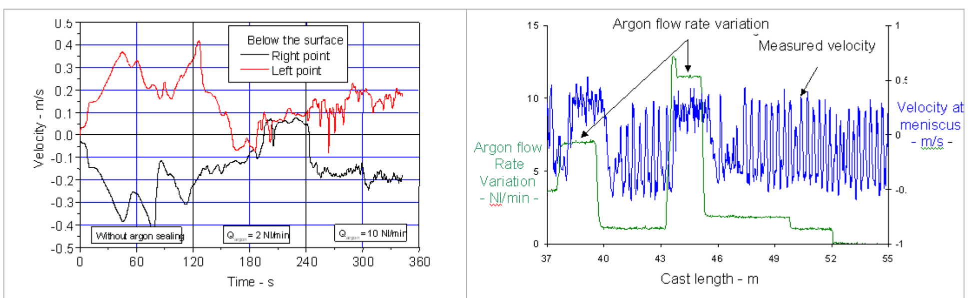


Figure 10 : Velocity fluctuations measured by SVC device at meniscus in the mould according to process parameters variation during the casting

Another application of the SVC sensor concerns the characterization of the argon injection in the SEN and its effect on the velocity fluctuation in the mould. In addition to the reduction of nozzle clogging, argon is injected into the SEN to control the flow pattern in the mould. The argon flow rate injected in the SEN is tested numerically (see case n°6 from Table 1 for simulation) in order to observe its influence on the stability of the flow in the mould. According to Figures 11a and 11b, we can remark that an increase of the argon flow rate reduces the velocity fluctuations in the mould. These numerical results are confirmed by the industrial trials.



a- Numerical results **b- Industrial results**

Figure 11 : Velocity fluctuations computed (a) and measured by SVC device (b) in the mould according to the argon flow rate injected : trends are similar

To maintain a stable flow in the mould, the argon flow rate should be kept safely below a critical level. Excessive argon injection may generate transient variations of the liquid steel jets entering the mould. Another negative effect is to increase the amount of gas in the nozzle area which influence the slag layer behaviour (possible emulsification). This will produce some thermal problems and some slag droplets carry away whose final effect is the generation of defects on final products.

- *Inclusions distribution*

Figure 12 represents inclusions distribution along the slab width according to their nature. Alumina inclusions are distributed over the whole width while slag inclusions are mainly centred. These numerical results are confirmed by industrial observations (see

Figure 5 and Figure 6). But as specified in paragraph I.3, the inclusions distribution is also depending on the casting conditions (casting speed, mould width…) and on their size.

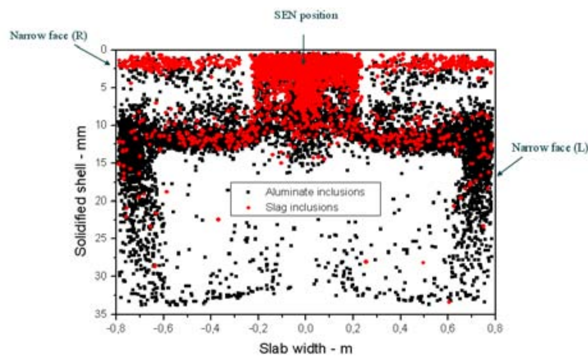


Figure 12 : Inclusions distribution in the mould width according to their nature : Alumina inclusions distributed over the whole width, slag inclusions mainly centred

4 PARAMETRIC STUDY

The idea of this third part is to put in evidence the effect of different process parameters on the type of flow pattern generated in the industrial mould and on its stability. In a previous publication (*Domgin et al.*, 2002), we have shown that the mould hydrodynamics, governed by the process parameters, is a key parameter for the steel cleanliness control in steady state.

Table 1 summarizes the different industrial configurations, in term of process parameters, tested numerically. The parameters in italic are those which vary in the simulations, in order to evaluate their influence on the steel flow in the mould. The liquid steel flow in the mould is defined in unsteady regime, the velocity fluctuations are characterised and analysed (Point located in 1/4 width and 20 mm below the meniscus).

Table 1 : Main characteristics of the simulated configurations

	Mould width - mm -	**Mould thickness - mm -**	**Casting velocity - m/min -**	**Immersion depth - mm -**	**Argon flow rate - Nl/min -**	**Nozzle design**
1°/ Flow pattern	1900	220	***1-1.25***	150	6	Flat type bottom nozzle
2°/ Vc	2000	229	***1-1.3-1.6-1.9***	160	7	Flat type bottom nozzle
3°/ Mould width	***1380-1540-1700***	220	1.1	150	6	Roof type bottom nozzle
4°/ Mould thickness	1540	***190-220-250***	1.1	150	6	Roof type
5°/ SEN immersion depth	1540	220	1.1	***110-150-180***	6	Roof type
6°/ Argon flow rate	1290	250	0.9	150	***0-2-10***	Roof type
7°/ SEN design	1540	220	1.1	150	6	***Roof and well type bottom nozzle***

4.1 Process Parameters Influence

The mould hydrodynamics, which is intrinsic to each industrial configuration, can be represented by the liquid steel flow and its turbulence. This parameter directly drives the behaviour of inclusions present in the liquid steel (*Zhang et al.*, 2006). The first requirement to improve steel cleanliness by the mould flow pattern control is to minimize transients during the casting operation.
An increase of the casting velocity (configuration n°1) completely modifies the flow pattern in the mould : passing from a single to a double roll flow pattern).

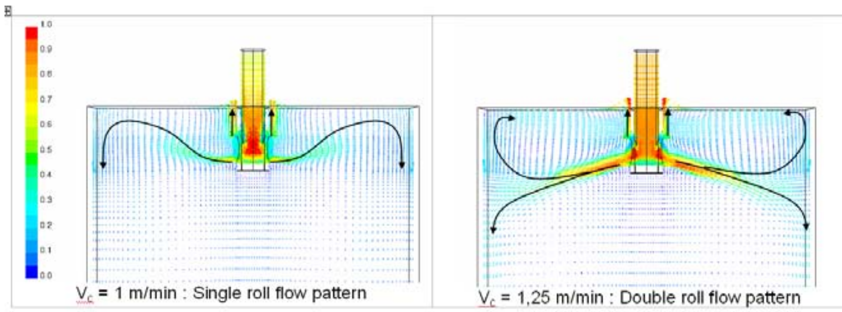


Figure 13 : Flow pattern modification in the mould - Industrial configuration n°1

Above a critical **casting speed** value, maintaining the type of flow pattern in the mould, an increase of this parameter induces an increase of the velocity at meniscus (Figure 14a), with some higher fluctuations and a higher risk of slag carry away. This increase can however have a positive effect since it generates important flow circulations near the solidified front and consequently allows a better washing effect (decrease in inclusion entrapment by the solidifying steel shell).
In these specific casting conditions, the effect of the **mould width** on the flow stability is very difficult to evaluate: the trends are not sufficiently pronounced (Figure 14b).
An increase of the **mould thickness**, by maintaining the casting velocity at a constant level, reduces the velocity fluctuations in the mould (Figure 14c). In such a situation, the metal throughput is higher and the liquid steel jet exiting the nozzle having a larger velocity is more stable.
A comparison of the sliver index obtained for industrial configuration with 2 thicknesses (*Rocabois et al.*, 2002) shows an average decrease of a factor of 2 for all steel grades concerned and for any slab width when the thickness is increased (passing from 190 mm to 220 mm). The reason of this influence is not fully understood except that this numerical simulation shows that the steel flow is stabilized when the thickness is increased. As the steel flow is more stable, the critical velocity for tear off by shearing is less often reached, so that less slag droplets should be formed and entrapped.
A lower **immersion depth of the SEN** induces larger velocity fluctuations with very large amplitude (Figure 14d). In such a situation, the critical value for slag carry away can be overreached, which is harmful for steel cleanliness. On the contrary, a higher immersion depth tends to stabilize the flow in the mould.
Some cares have to be taken with an excessive immersion depth, which can have some impacts on the thermal behaviour of the meniscus with some possible parasitic

solidification (meniscus freezing) and new generation of casting problems (longitudinal cracks, breakout…).

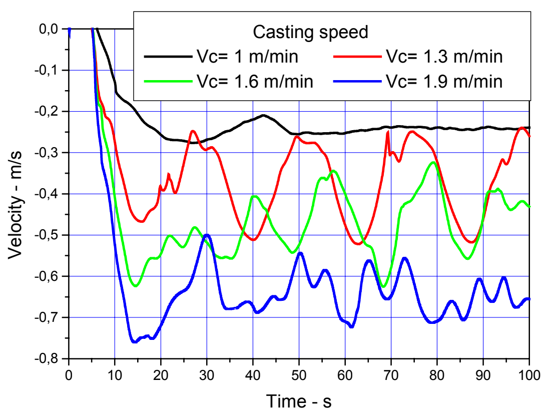
The **SEN design** modifies the steel flow directly in the nozzle and consequently the flow in the mould. They are likely to produce a different fraction of steady and unsteady steel flow. The roof type bottom nozzle, compared to the well type ones, produces a higher level of velocity, in term of intensity and in term of fluctuations (Figure 14e). This can have two main effects on the inclusions behaviour :

- a higher level of velocity and fluctuations just below the meniscus can result in larger mould slag droplets torn off and spread in the liquid steel,
- due to a higher intensity of velocity, the washing effect is more pronounced and is beneficial to avoid inclusions entrapment by the solidified shell.

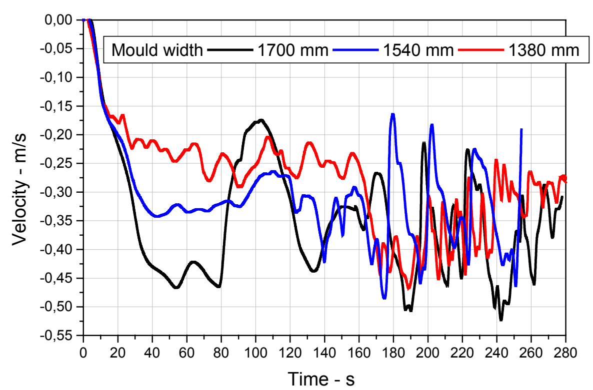
On the other hand, the well type bottom nozzle produces a lower level of velocity in the upper part of the mould which can influence the thermal behaviour of the steel in this part and can induce some thermal heterogeneities and some parasitic solidification at the meniscus.

According to these results obtained with our numerical tool, we can say that numerical simulation gives some information concerning the behaviour of the liquid steel flow in the mould and its impact on the steel cleanliness. In a similar way, *Brummayer et al.* (2000) have used such a numerical CFD tool in order to optimise the SEN for a better stabilization of mould fluid flow in a wide slab caster.

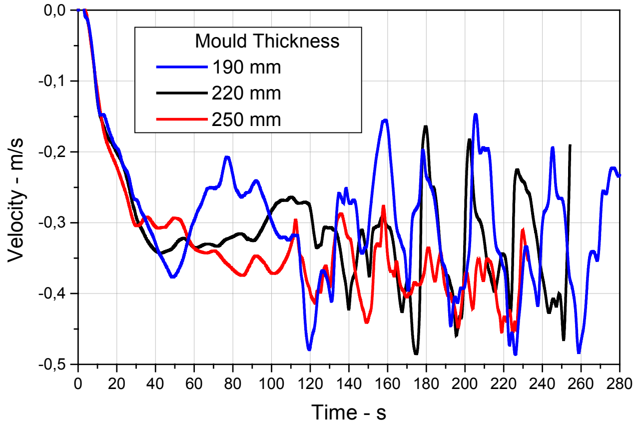
Numerical results presented in paragraph 4.1 are specific to the casting conditions tested. That is why a numerical validated model is a very useful tool to make such parametric studies.



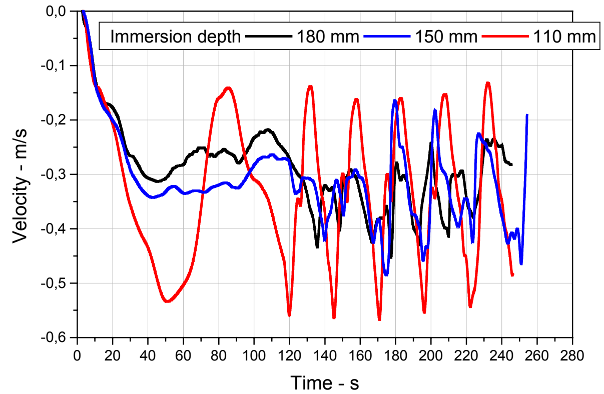
a- Casting speed



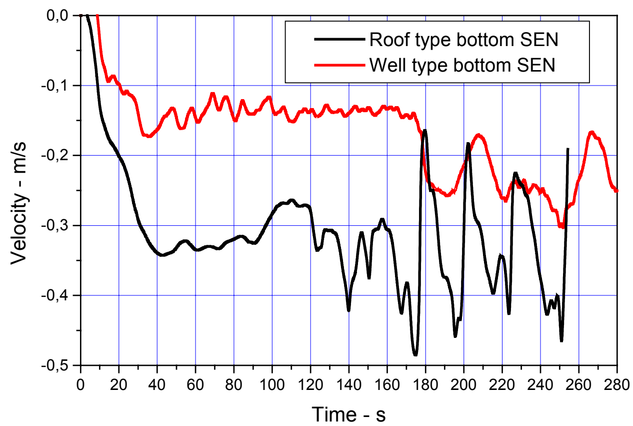
b- Mould width



c- Mould thickness



d- SEN immersion depth



e- SEN design

Figure 14 : Effect of process parameters on meniscus velocity fluctuations

4.2 EM actuators Influence: Example of the EMLA Mode

The coupling between electromagnetic field and hydrodynamics (paragraph 3.1) is applied in this part to study the influence of an electromagnetic actuator in the CC mould. Such a type of actuator precisely located around the mold can drive the liquid metal flow inside the mold and decrease the defects rates in the slab (*Kubota et al.,* 2001). The actuator modeled is in EMLA mode (ElectroMagnetic Level Accelerator) and is usually used to increase the fluid velocity inside the mold for relatively low casting velocity.
Figure 15 shows the increase in the horizontal velocity (1/4 width and 20 mm below the meniscus) when the EMLA mode is applied in the mould for Vc = 1m/min: the mean horizontal velocity increases from 0.2 to 0.45 m/s.

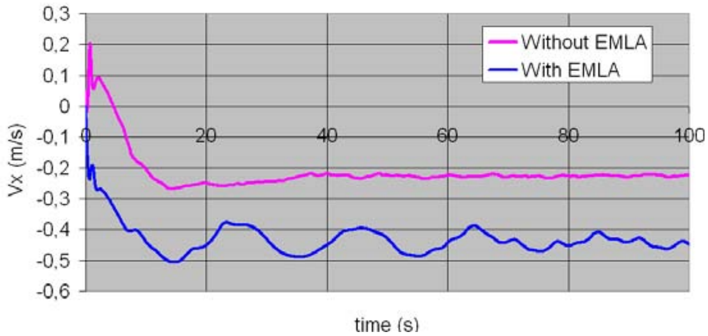


Figure 15 : EMLA influence on horizontal velocity below the meniscus for Vc = 1 m/min

The Figure 16 puts into evidence some slight differences on meniscus temperature between the standard configuration and the EMLA configuration:

- the mean temperature is slightly higher with the EM actuator (1539.5 °C versus 1538.5 °C in the standard configuration): the EMLA mode allows a larger renewal of hot metal coming from the SEN;
- the cold zones appearing in the standard configuration are diminished when the actuator is activated and the decrease in the risk of parasite freezing of the meniscus should lead to a decrease in the risk of breakthroughs.

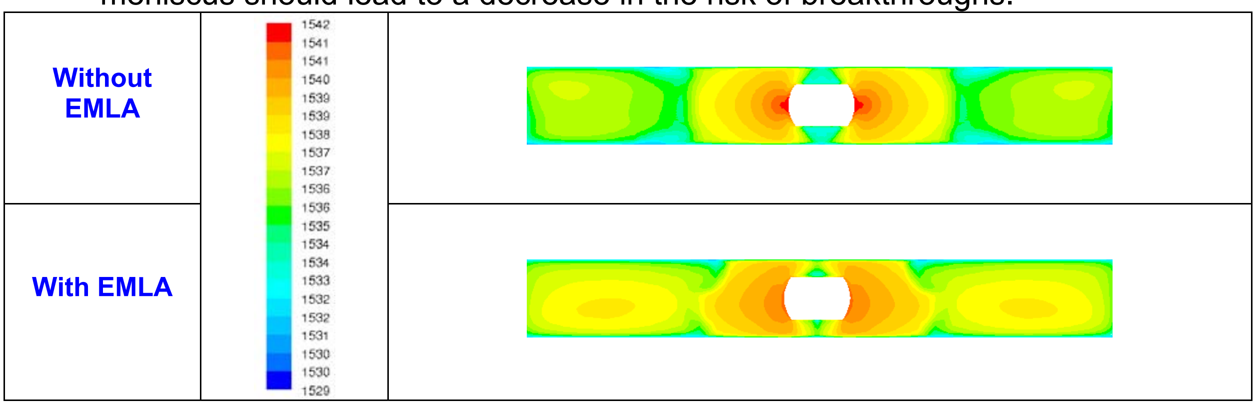


Figure 16 : Temperature levels at the mold surface : EMLA influence for Vc = 1 m/min

5 CONCLUSION

A numerical tool has been implemented at Arcelor Research to evaluate the influence of different process parameters (nozzle design, immersion depth, argon flow rate, slab thickness...) on the stability of the flow in CC mould and on steel cleanliness. It appears through these several numerical tests, confirmed by industrial measurements, that the hydrodynamics, which is the key parameter to improve steel cleanliness, generated in the mould is naturally unsteady, even maintaining the process parameters at a constant value in these simulations. In order to maintain a stable mould flow that encourages inclusions removal while avoiding the generation of new defects, process parameters should be optimized or some actuators have to be proposed and adapted (EM actuators for example). For this reason, numerical modelling is a very useful tool to get a good knowledge of the phenomena developing in the CC mould when the process or geometrical parameters are changed.

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