AN INNOVATIVE INTEGRATED METHOD IN MHD DESIGN OF ELECTROMAGNETIC STIRRERS

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ABSTRACT

Design and optimization of stirrers are complex activities for two main reasons: there is no standard in steelmaking plants, meaning that a personalized design is typically required, and it is not possible to accurately predict the flow induced to liquid steel in the mould. To overcome these complexities two ways can be followed: experimental analysis on scale models and computer-aided numerical simulation. On these basis Ergolines Lab has developed a new design and simulation software tool which is capable to provide engineering solutions and process optimization in times compatible with design requirements, and that can lead to better metallurgical results and lower energy consumption.

This paper describes an example of analysis made on a billet caster production facility. In particular, the following has been evaluated: influence of electric operating parameters (current and frequency), influence of process parameters (casting speed and type of entry nozzle adopted).

KEYWORDS

MHD, electromagnetic stirring, stirrer, numerical simulation, parametric study.

INTRODUCTION

An increasing demand for higher-quality steel has made the stirrer an essential component in the continuous casting process. The flow induced by electromagnetic stirrers into the liquid steel produces numerous benefits; for example, an increased thermal exchange, with consequent growth of equiaxed zones during solidification, and a significant reduction of porosities, inclusions and carbon segregation.

The evolution of continuous casting machines requires a parallel extreme evolution in the performance of stirrers that, not being a standard off-the-shelf product, must be optimized and custom-designed for each plant so as to achieve top results in terms of both metallurgical performance and energy savings, given the high cost of electric power.

As a result, the design of stirrers becomes a delicate and committing task, in particular because it is quite difficult to foresee their effect. In-fact, it is almost impossible to accurately verify steel flow patterns in the mould by means of direct measurements, and the choice of the operating parameters is mostly the result of field experience.

Two ways can therefore be followed to analyse the fluiddynamic and metallurgical effects of stirrers: experimental analysis on scale models and computer-aided numerical simulation. However, the realization of scale models is very complex (e.g. compliance of similitude parameters with both electromagnetic and fluiddynamic engineering), very expensive (in time and cost) and most-of-all inadequate to satisfy the present demand for fast and flexible design procedures.

All these considerations formed the idea of developing a numerical simulation tool capable to provide the necessary information for a correct design and optimization of Ergolines' EMS machines in a reasonably short time and with limited cost.

1. OUR CHOICE

Currently available computing tools for electromagnetic stirrer design and evaluation are inadequate and, in most cases, they reveal to be purely academic studies, quite far from industrial reality. Simulations are particularly complex, and this is for two reasons:

- there is no commercially available software package that can accurately solve both electromagnetic and fluiddynamic tasks in a way compatible with design requirements;
- the solution of the fluiddynamic task is particularly difficult.

Ergolines Lab has developed a numerical simulation tool from a well-established commercially-available simulator, supported by an open-source fluiddynamic package. The choice for an open-source code has provided significant advantages, allowing to directly control simulations, optimize computation tasks, achieving the best integration of the two packages.
The simulation process can be summarized in the diagram shown in fig. 1.

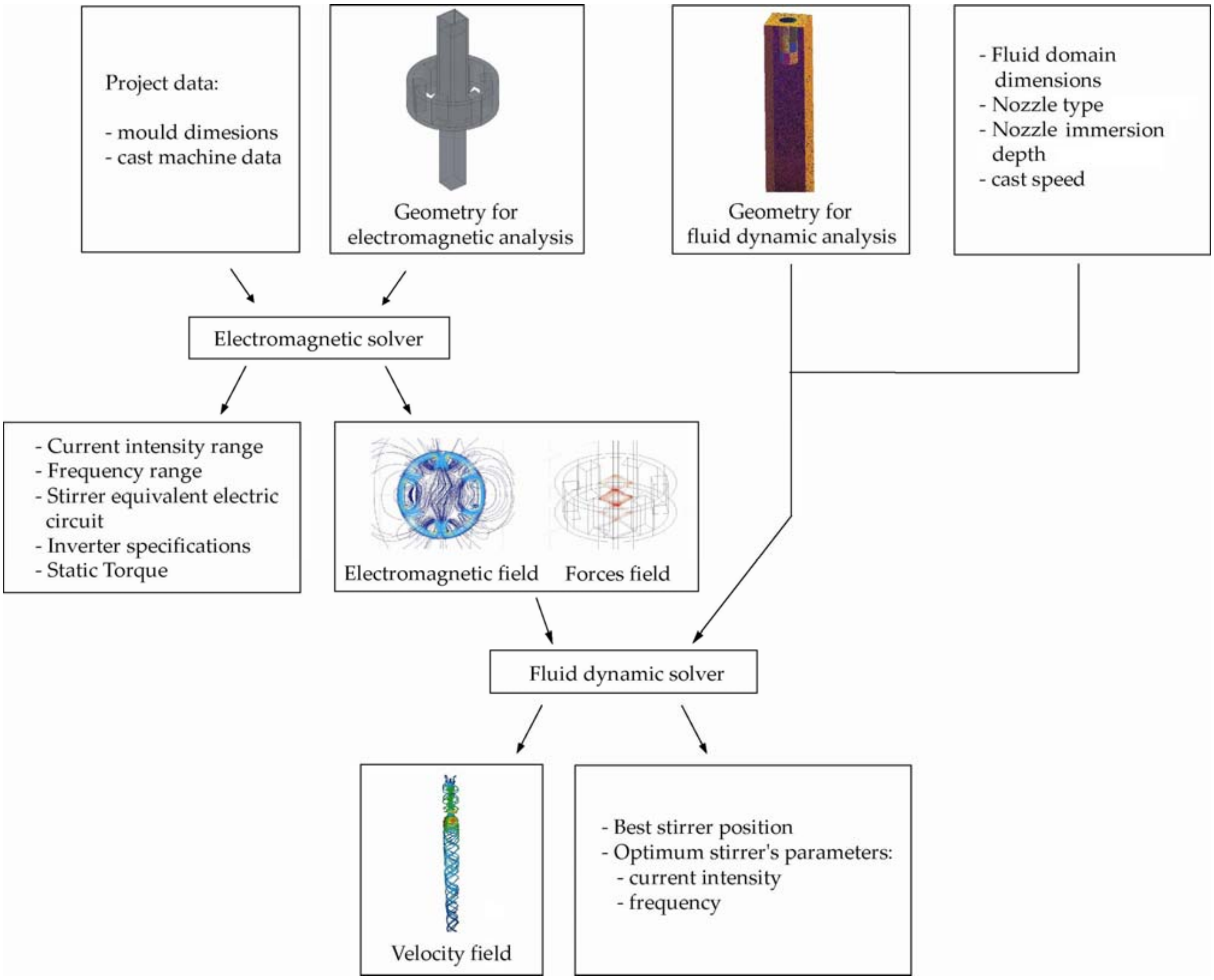

Fig. 1 Project tool “work flow”

The system for electromagnetic computation is composed of the stirrer, the fluid domain and the mould, whose modelization plays an important role, being the copper wall a major shield against the electromagnetic field in both intensity and direction. Once current and frequency of the stirrer are assigned, the electromagnetic solver operates a "time harmonic" analysis and provides a solution of the electromagnetic induction equation by calculating the magnetic field, the induced currents and the Lorentz forces. The forces are exported by the electromagnetic application and imported as volume forces by the fluidodynamic open-source code, because, for low magnetic Reynolds number, the coupling is weak. The application developed by Ergolines is a CFD steady-state solver with SST (Shear Stress Transport) turbulence model [1].

Two assumption were considered:

- surface tension of meniscus is not included in computations;
- thermophysical properties of molten metal were considered to be constant, neglecting the solidification phenomena.

The complexity of interpretation of mould flow data has required to develop a Matlab®-based visualization routine, which allow designers to quickly analyze simulations by means of specific diagrams emphasizing most interesting phenomena and variables like, for example, rotational velocity and frequency of steel, the slip factor between fluid and rotating magnetic field and the extension of secondary recirculation flows.

The total computing time for the whole process is approximately one week using a commercially-available workstation.

2. MODEL VALIDATION

Several experimental tests have been conducted to validate the reliability of simulations; these have been run with a prototype scale stirrer, using mercury and Wood-alloy (hot test) as test fluids.

Figure 3 shows the test equipment. The scale stirrer (figure 2) is a prototype based on a tri-phase stator with 80 mm external diameter. The stirrer is fed by an inverter with adjustable current and frequency. The inverter is powered by a variable-voltage supply. In order to avoid over-heating the coils, the stirrer has been placed inside a plexiglass tank with flowing water.

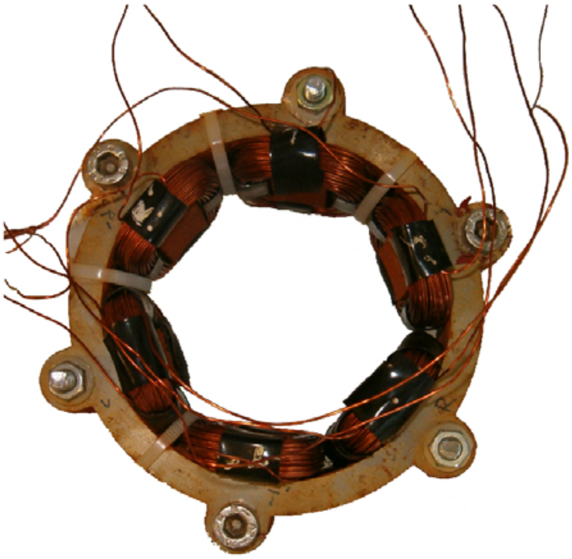

Fig. 2 Prototype stirrer for validation tests.

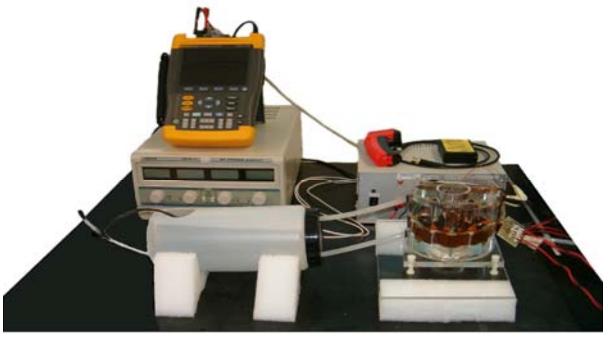

Fig. 3 Validation test instrumentation.

Before the actual test, a measure of the magnetic field has been made using a Hall probe. During the test a video camera placed on the stirrer axis has recorded the velocity profile on the surface of the fluid; the recordings have been compared with the numerical computation.

Figures 4 and 5 show a comparison between the measured and the simulated magnetic field and the velocity profile of one of the tests run on mercury.

To give consistency to the results, several current intensities have been tested, always obtaining profiles strictly comparable to those shown below. This has proved that the tool developed can accurately predict the flow induced by the stirrer into the fluid.

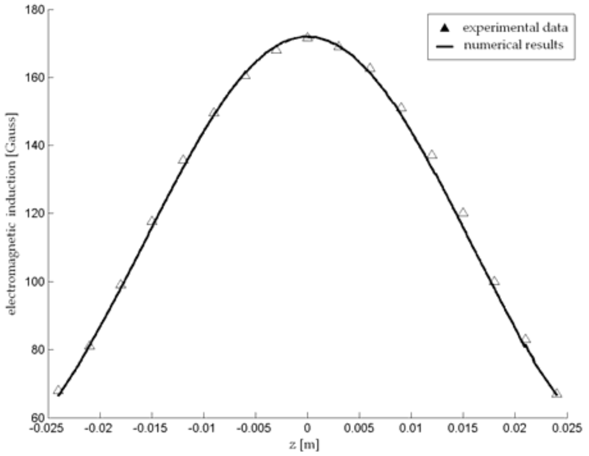

Fig. 4 Comparison between calculated electromagnetic induction and experimental data.

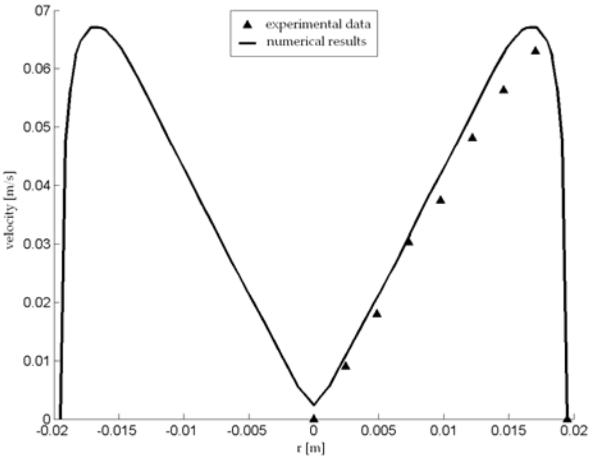

Fig. 5 Experimental an computed velocity profile on mercury surface.

3. CASE STUDY

To further demonstrate the effectiveness of the tool developed, a case study was conducted on a typical M-EMS-equipped continuous casting mould. Process data are shown in Table 1.

Table 1 Process data and simulation parameters

Process data:	cast size casting speed type of entry nozzle	145x145 mm 1.2 m/min four-port
Study parameters:	effect of current effect of frequency casting speed type of entry nozzle counter-stirrer	(50 - 400 A) (1 - 7 Hz) (0.6 - 3.6 m/min)

3.1. ELECTROMAGNETIC ANALYSIS

Figures 6 and 7 show the results of electromagnetic analysis, in particular the magnetic field and force field patterns.

In fig. 6 it is interesting to observe the influence of the mould on the space distribution of magnetic field lines. The shielding effect of the mould, due to the high electric conductivity of copper, deviates the magnetic field and produces increased uniformity inside the mould. About the forces, it is to be noticed their distribution on planes perpendicular to the stirrer axis and their rotational pattern inducing rotational flow in the steel.

In addition to field and force distribution, the electromagnetic software allows to calculate the curve of static torque (see fig. 14), the inductance of the stirrer and the losses caused by the mould.

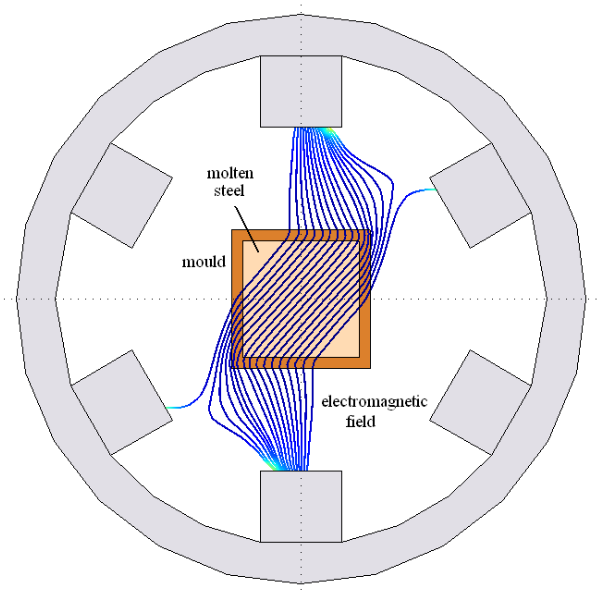

Fig. 6 Electromagnetic field.

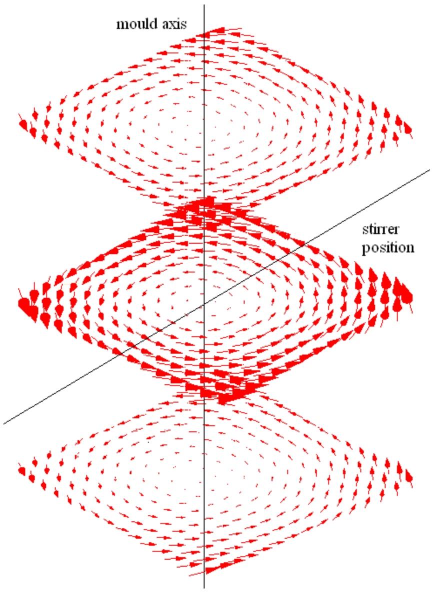

Fig. 7 Force field inside the mould.

3.2. FLUIDDYNAMICS ANALYSIS

As contemplated in the literature [2, 3] the fluiddynamics simulations have shown that rotational stirrers induce two types of flow: the main "swirl" flow (see fig. 8) and a very important secondary axial flow (see fig. 9).

The first is generated by the rotating forces induced by the stirrer. The centrifugal force caused by the swirl flow generates a low-pressure zone in the centre of the stirrer. This causes two opposite vertical flows, one from the top and one from the bottom, heading to the centre. This generates the so called secondary flows, which develop axially and reveal to be very important because they remarkably increase thermal exchange with the mould.

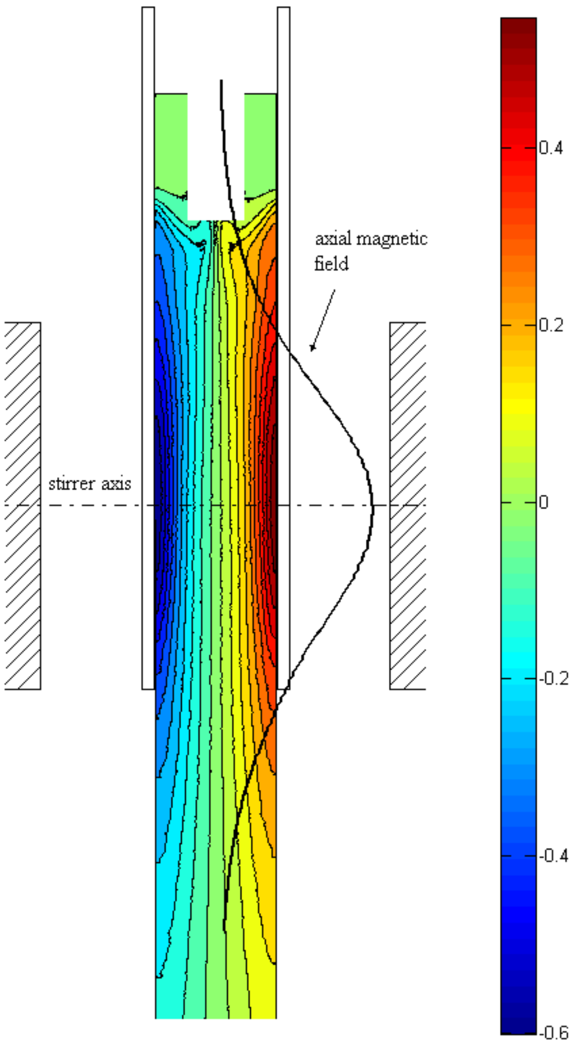

Fig. 8 Swirl flow: tangential velocity [m/s].

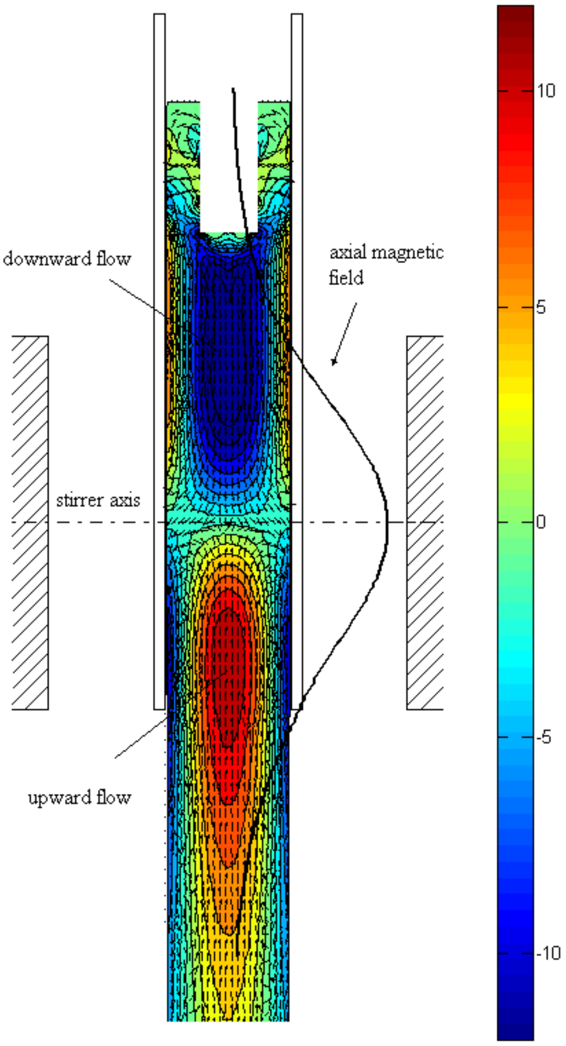

Fig. 9 Secondary flow: axial velocity [m/min].

3.3. CURRENT INTENSITY VARIATION

In accordance with the analytical theory [2, 4]), it was noticed that the velocity pattern is linear versus the magnetic field and therefore versus current (figure 10).

Also the secondary flows are subject to a linear dependence (figure 11), except for an interesting phenomenon: the velocity vs. current diagram in fig. 10 shows that the line passes through the origin, meaning that at zero current, the tangential velocity is also zero. However, the diagram in fig. 11 shows that the line intersects the x-axis slightly above 50 A, meaning that below a certain current intensity the secondary flows cannot develop.

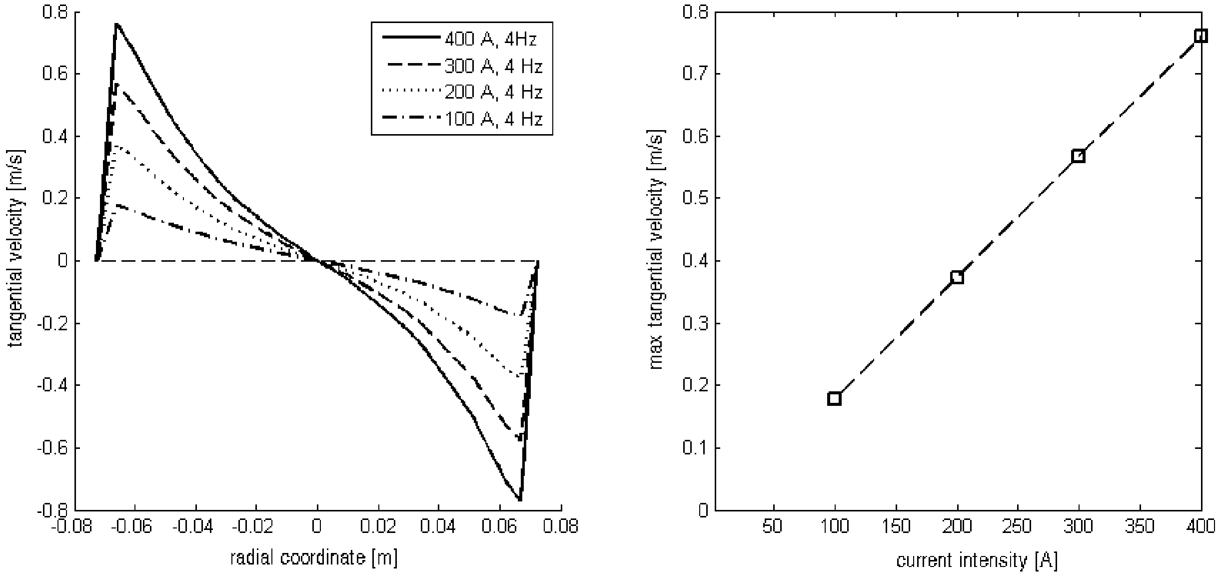

Fig. 10 Tangential velocity in the centre of the stirrer. The relation between the velocity and the current intensity is linear.

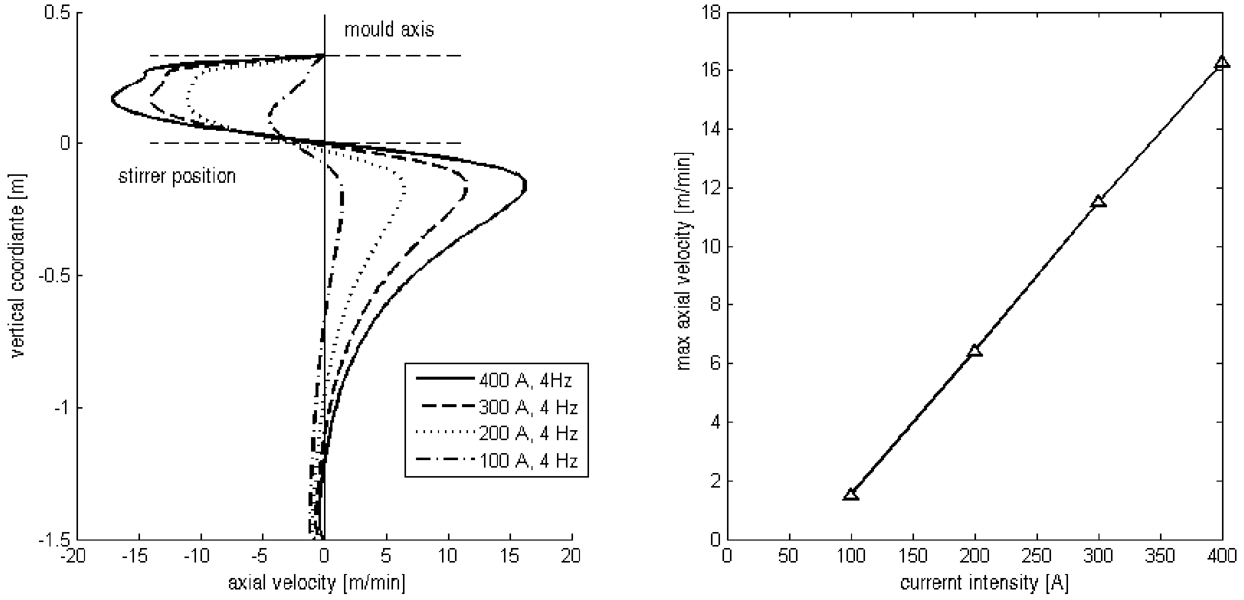

Fig. 11 Axial velocity along the stirrer axis. The relation between the velocity and the current intensity is linear.

3.4. FREQUENCY VARIATION

The correlation between rotational velocity and frequency of the magnetic field (figure 12) shows two aspects: the first is that, at a given magnetic field, the function is proportional to $\sqrt{f}$ (shown in figure 13 and analytically calculated in literatures [1, 3]. The second is that the velocity profile reflects the behaviour of the static torque curve, meaning that the torque is particularly indicated to characterize the operating space of the stirrer (figure 14).

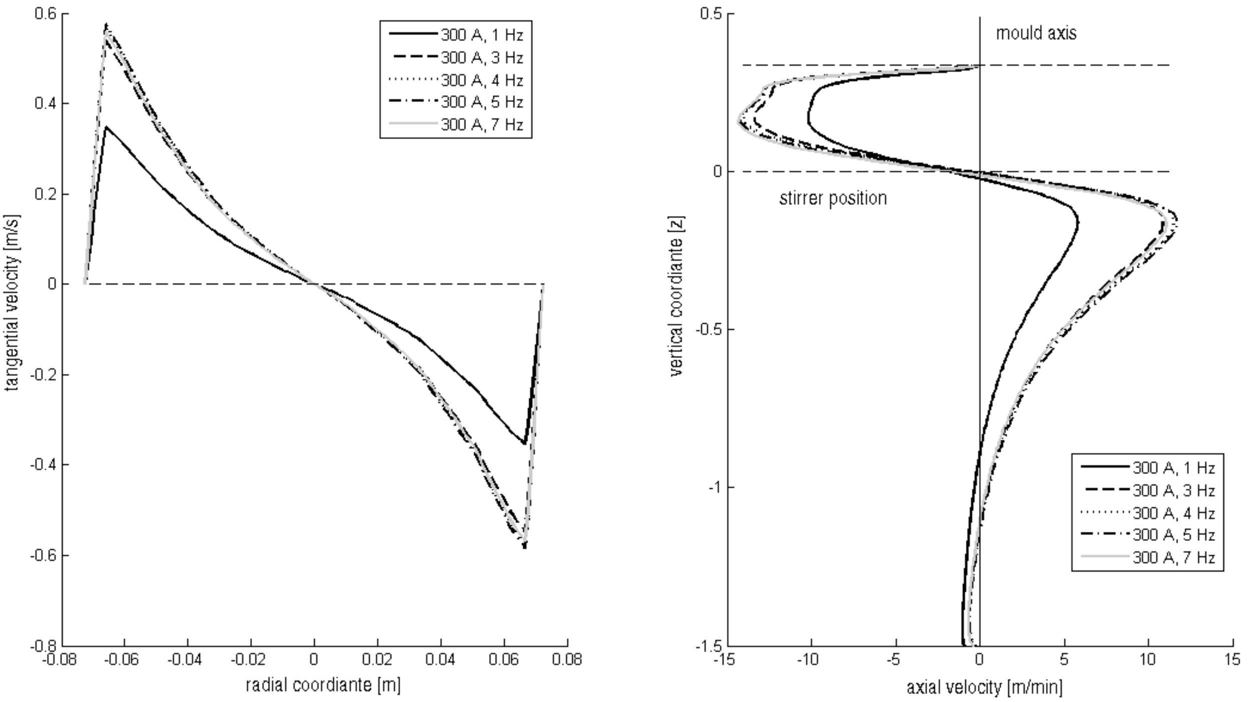

Fig. 12 Velocity profiles at different frequencies.

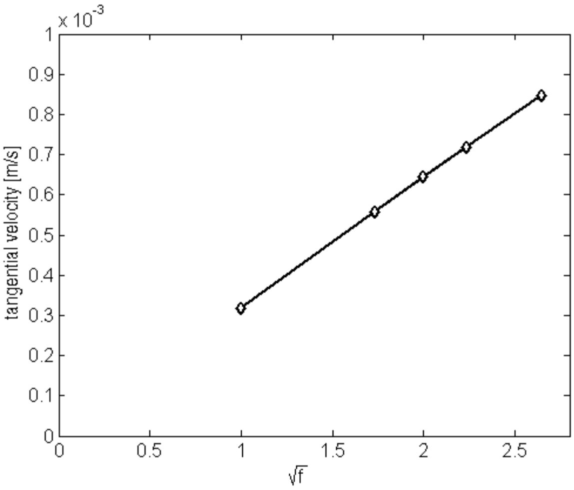

Fig. 13 Relation between tangential velocity and frequency.

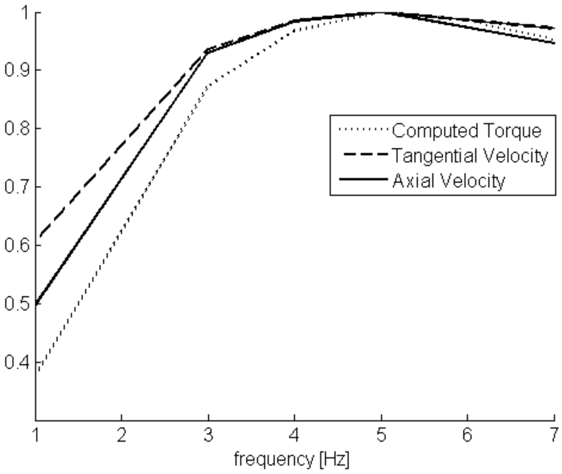

Fig. 14 Velocity and torque profiles.

3.5. CASTING SPEED VARIATION

The tool has not been developed exclusively for design purpose. In-fact it reveals to be also a powerful mean to verify and predict the effect of the stirrer at varying process parameters.
For example, the effect of a steel flow change on the patterns induced by stirrer was studied.

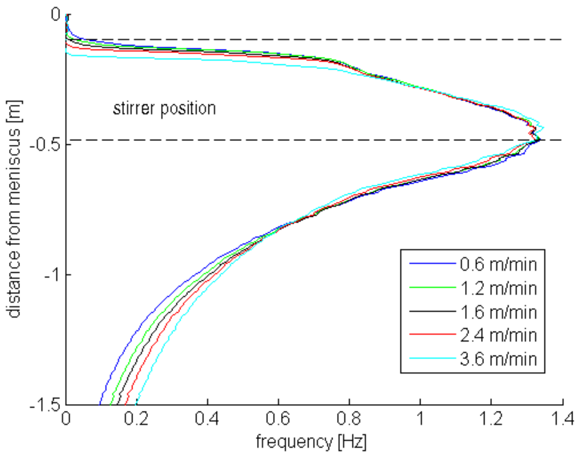

Fig. 15 Steel rotation frequency.

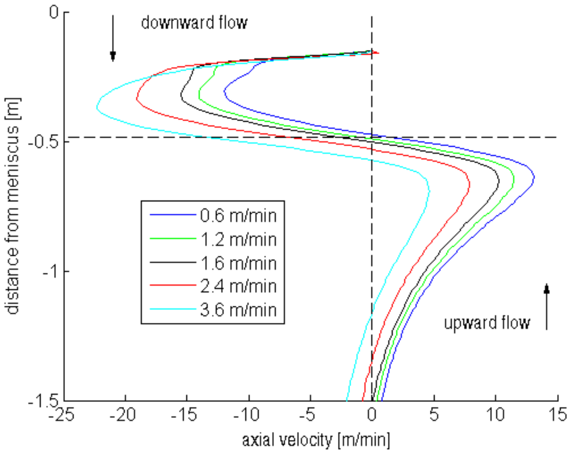

Fig. 16 Axial velocity along the stirrer axis

Figure 15 shows how the rotational velocity of the steel is not particularly affected by the casting speed. Only in the zone close to the surface it can be noticed a lower influence of the stirrer. As regard to the secondary flows, the influence of steel flow is particularly noticeable. Figure 16 clearly shows how the “S” of velocity moves to left, meaning that the velocity increases above the stirrer and the upward flow decreases. By plotting the maximum values of upward velocity and those of lower recirculation extension (normalized at 0.6 m/s casting speed), it is possible to observe a linear dependence versus casting speed (figures 17 and 18).

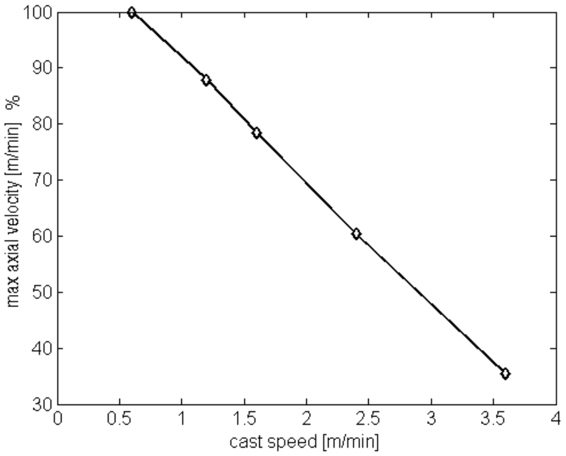

Fig. 17 Axial velocity maximum.

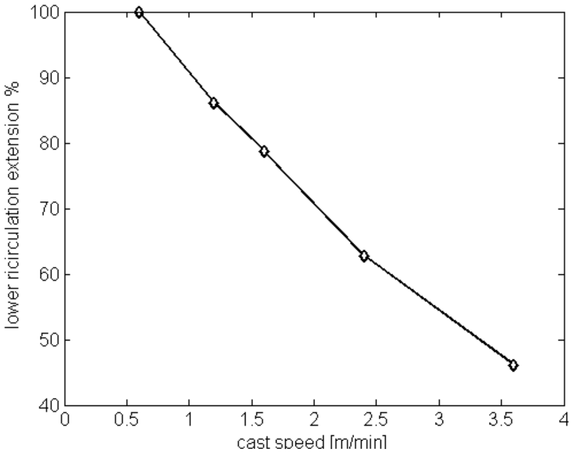

Fig. 18 Lower recirculation loop extension.

3.6. TYPE OF ENTRY NOZZLE

The study has covered the analysis of flow with both single-port and multi-port submerged entry nozzles; in particular, a four-port nozzle with 15° upward inclination has been modelized. The analysis has shown that the type of nozzle does not influence steel flows below the stirrer in a significant way (figure 19), nor in terms of tangential velocity or in terms of secondary flow recirculation extension. This shows that the stirrer is sufficiently powerful to force the steel flow, regardless of upstream conditions.

The same happens also above the stirrer, in the zone between the nozzle tip and the stirrer: no influence from the four-port nozzle is observed on the rotational flow, allowing for a good extension of the stirrer effect towards the top (figure 19).

Only in the zone between the nozzle tip and the free surface things are slightly different (Figure 19): here the steel flow stops the helicoidally flow thus causing a much slower rotational velocity at the meniscus level (figure 21).

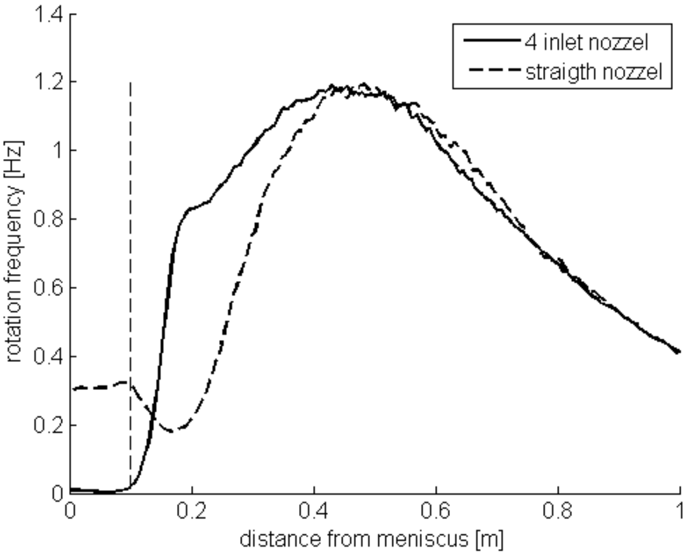

Fig. 19 Steel rotation frequency.

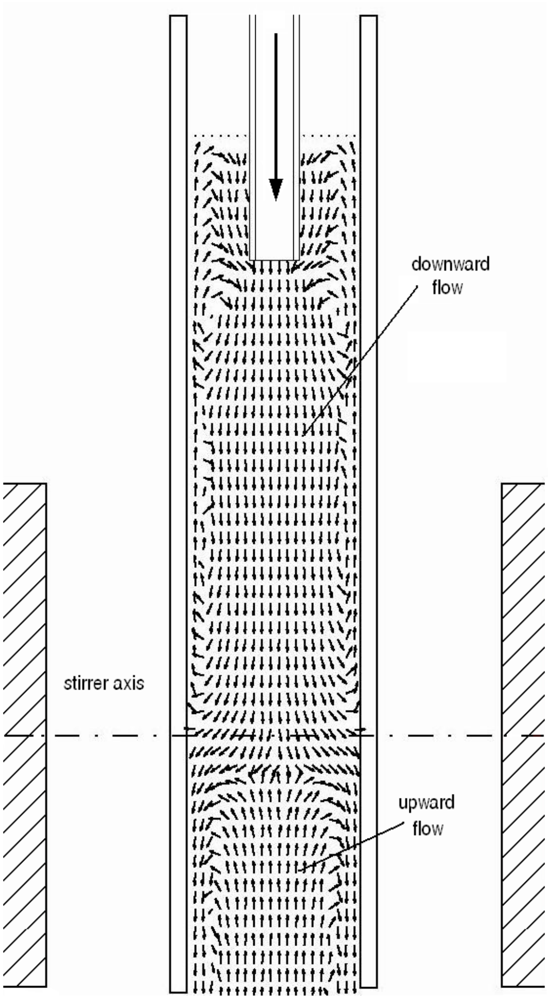

Fig. 20 Standard one-port nozzle.

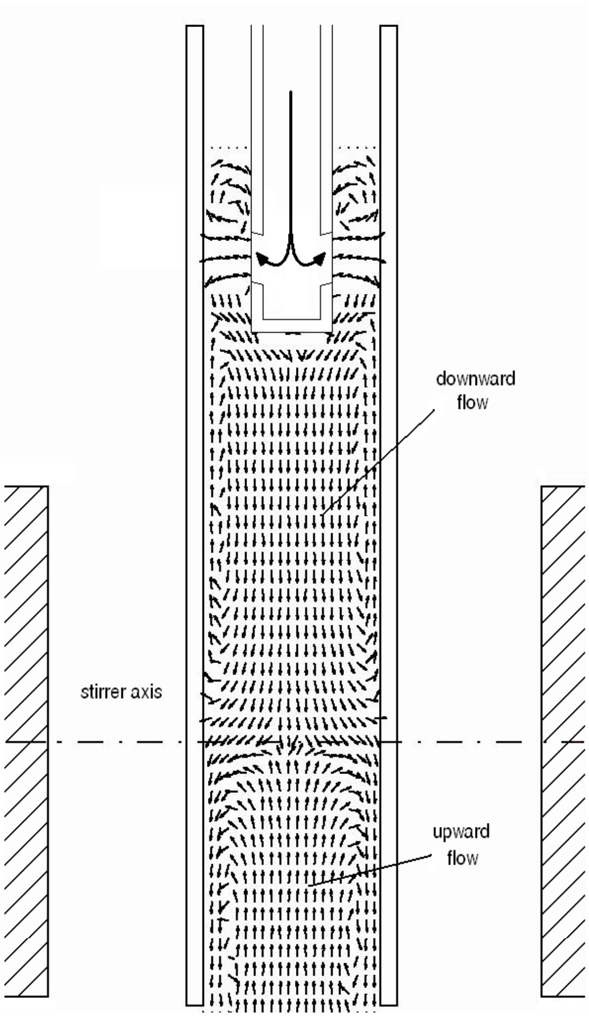

Fig. 21 Four-port nozzle.

3.7. ELECTROMAGNETIC STIRRER AS A BRAKE

Last function allowed by the tool developed is the ability to simulate the presence of a second stirrer, having opposed field (counter-stirrer), and evaluate the efficiency of the main stirrer.
The simulation process is that already explained, including the ability to simulate rotational fields at different frequencies.
Like before, the domain can be subdivided in several zones influenced by the braking "counter-stirrer". It can be noticed that below the stirrer, flows are not affected by the brake because the amount of fluid subject to the magnetic field is too small to generate a pressure differential that can affect the secondary flow. In the zone between the main stirrer and the brake, the tangential flow is significantly limited by the counter-stirrer. Finally, the zone above the brake, i.e. at meniscus level, is almost exclusively controlled by the brake. Figure 22 shows how the rotational flow of steel above the brake is even reversed.

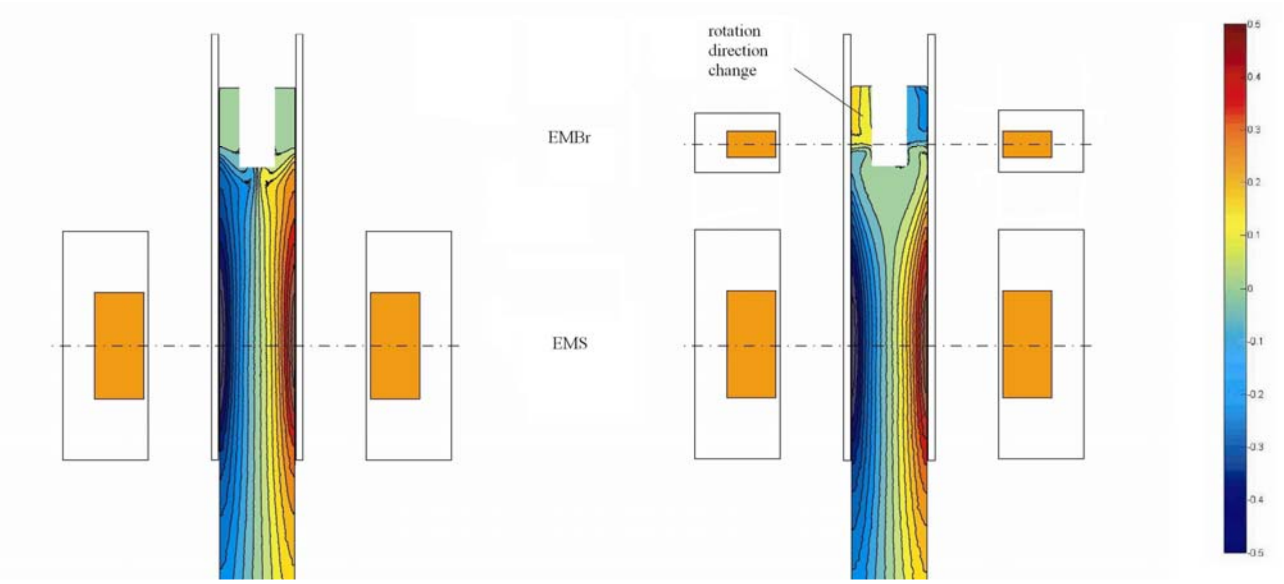

Fig.22 Tangential velocity in simulation with and without EMBr.

In summary, it can be stated that:

- the use of the counter-stirrer does not modify the secondary flow extension induced by the main stirrer;
- the stirring effect between the brake and the main stirrer is reduced;
- the counter-stirrer can modify the rotational velocity at meniscus level, though this possibility is very complex to operate.

4. CONCLUSIONS

The tool developed demonstrates to be a very effective aid during design stages of stirrers. Thanks to specific simulations, it is possible to operate a complete parametric analysis of any casting facility, in order to establish the most appropriate operating current and frequency and guarantee the best metallurgical performance. At the same time, also the power requirement is optimized, thus minimizing energy consumption. In addition, this tool can be used to predict any process behaviour changes caused by any variations in the operating parameters like, for example, casting speed or type of entry nozzle, providing valuable information to tune the electric settings of the stirrers and optimize metallurgical results.

Further developments of the tool will include to consider variation of thermophysical properties vs. temperature and solidification phenomena.

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