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Experimental approach to develop Multi-Mode® EMB, an advanced electromagnetic brake for thin slab casters

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Abstract

This paper refers to the development of a new electromagnetic brake (Multi-Mode® EMB) specifically dedicated to thin slab casters (TSC). Unlike our first publication last year [1] it describes in more detail the approach to develop a new EMB concept not only by simulations but by experimental work. Considering that no commercial software was available with reliable full coupling between electromagnetic and CFD codes and starting from our know-how in TSC process fluid-dynamics, we decided to design and realize an installation that simulates with cold melting metal at scale 1 the industrial operation of a thin slab caster. The result was not only the validation of the concept of the new EMB, but the development of the operating know how. The extensive measurement of liquid metal flow velocity and fluctuations within a large range of existing and future operating conditions of slab width and casting speed permits to develop in advance the knowledge, how to use the EMB control parameters for different casting conditions. That in turn permits to develop in advance the automation software for industrial operation. Without the full scale caster simulator, such task would require test casts of some hundred thousand tons that no steel making company would accept to do on its thin slab caster.

Key words: EMB, EM Brake, Thin Slab Caster, response surface methodology

Introduction

The quality of continuously cast slabs is strongly related to the liquid steel flow in the mold. Various technologies of Electromagnetic Actuators (EMA) are currently used on continuous casting machines to control the steel flow. For conventional (medium to thick) slabs, different concepts using electromagnetic stirring (EMS) or electromagnetic braking (EMB) are competing, whereas for thin slabs, up to now conventional EMB like EMB_r or EMB_r-Ruler [2] with one or two poles per mold are used. These provide only a global braking action, but the specific problems of high productivity thin slab casters require a more differentiated action. We have explained in a recent paper our concept why for medium and thick slabs we recommend EMS (our Multi-Mode® EMS technology) and why specifically for thin slabs we have developed a new EMB technology [1, 3].

Due to the particular geometries of the funnel mold (Fig. 1) and the submerged entry nozzle (SEN) (generally with four ports, Fig. 2) of thin slab casters, the predominant flow pattern is the Double Roll characterized by two lateral recirculation loops toward the meniscus two lateral downward jets penetrating inside the liquid pool and one upward central returning flow (Fig. 2).

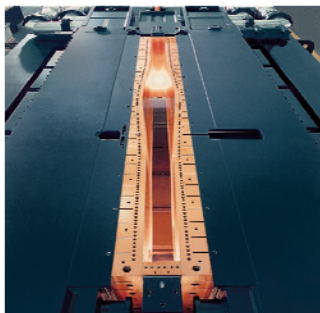


Fig. 1: Danieli's Funnel mold design for thin slab Casters

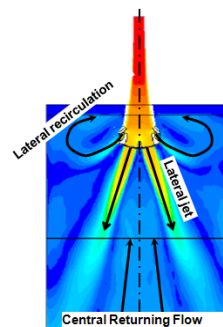


Fig. 2: Double-Roll in Thin Slab Casters with 4 ports

Like in conventional slab casters, the lateral recirculation loops and the downward jets become too fast at high casting speed/high throughput and must be slowed down by a **braking function**, however in thin slab casters the aim is to differentiate the braking function between the upward and downward flow. Also like in conventional slab casters, right/left asymmetrical and unstable flow must be prevented by a **stabilizing function** that prevents bias flow and flow

switching from right to left. However, unlike conventional slab casters, vertical meniscus fluctuations become more severe in thin slab casters due to the reduced mold volume, and that requires a **damping function**.

To address these specific flow problems of thin slab casters, an EMB with a multiple pole geometry and three distinctive functions braking, stabilizing and damping (Fig. 3) has been developed by Danieli Research Center and Danieli Rotelec and is commercialized under the name Multi-Mode® EMB.

The slab quality problems related to the flow control functions have been explained in more detail in a previous paper [1]. The purpose of this paper is to show that both, extensive computer modeling as well as important experimental work are necessary to achieve such industrial development.

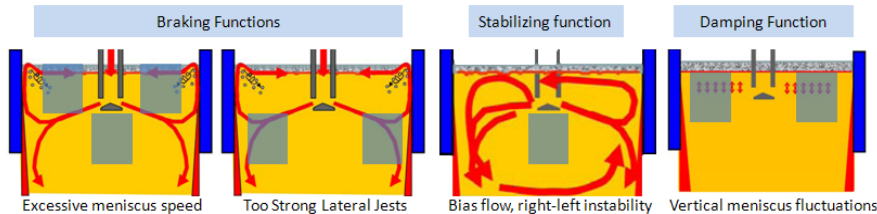


Fig. 3: New Danieli Multi-Mode® EMB multipole configuration

Why modeling is useful but not sufficient ?

EMB, in contrast to its name and to a widespread opinion, does not really brake the liquid steel velocity, but more likely deviates or deflects the steel flow.

With our purpose to develop a new EMB with distinctive functions, a multi-pole geometry is proposed. To find the ‘good’ pole geometry, we have started the development with modeling the concept, i.e. to compare and choose for a wide range of flow topology the number, size and position of the poles and the required ampturns of the coils.

Modeling is a powerful and useful tool to investigate and choose between various solutions for complex multi-physics problems. In our case, a one way modeling between Electromagnetic Brake and stationary fluid dynamics (CFD) provides a qualitative description on how the steel flow ‘responds’ to different magnetic configurations.

However, it does not provide a reliable quantitative information. In order to increase the accuracy of such modeling and to approach reality, it is necessary to use transitory CFD method which is very time consuming compared to stationary method and which must be calibrated by experimental measurement data. Moreover, to describe the operation of a caster, the number of simulations would be too big and the time required to perform such work too long. As an example, if we consider just one mold design and one SEN geometry, we would have to compute at least 450 cases (5 casting speeds from 4 to 8 m/min times 9 slab widths from 1000 to 1800 mm times 10 different coil current settings). For all the above reasons, we felt necessary to validate the new EMB experimentally and decides to design, manufacture and operate a thin slab simulator plant with full scale EMB and full scale thin slab funnel mold.

Full scale caster simulator

Based on the concept development by modellisation, an EMB prototype was designed and manufactured by Danieli Rotelec in France, and a 1:1 scale low melting metal facility was designed and installed in the Danieli R&D Center in Italy (Fig. 4).

The steel flow conditions have been reproduced by a recirculation loop of cold melting bismuth-tin alloy (melting point 138°C), which has physical properties such as conductivity, density and viscosity very similar to liquid steel. On the top of the facility a small tundish and an industrial stopper provide the liquid to the SEN and the mold. Below the mold, the low metal alloy is collected in a special tank designed to prevent turbulence transmission up to the mold; it then is recirculated upwards by means of a centrifugal pump having an operating range from 450 l/min to 1100 l/min (casting speed range from 4.2 to 11.7m/min).

A real full scale copper mold with funnel geometry and variable width from 990 mm to 1800 mm (Fig. 4) is used. The slab thickness at narrow face has been kept constant at 102.5 mm. The MM-EMB is installed on both sides of the mold. Real refractory SEN with different geometries have been used for the tests.

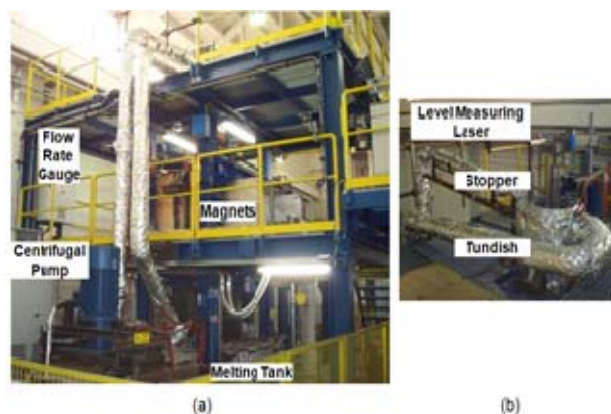


Fig. 4: (a) Low melting metal simulation facility in Danieli R&D Center (Buttrio, Italy), (b) Detail of the small tundish

Experimental Work

The experimental set up is composed of four sensors (Fig. 5). Two velocity sensors, so called "paddles", are immersed on each side of the SEN and monitor the right and left horizontal meniscus velocities. On the left side, vertical meniscus fluctuations are measured by recording the position of a floating sensor installed on the left side of the mold (Fig. 5&6). Each 40s sliding windows, the standard deviation (σ) of the meniscus waviness (horizontal fluctuations) is determined and is available online. On the right side, a meniscus topography is obtained by a laser scanner (Fig. 5&6).

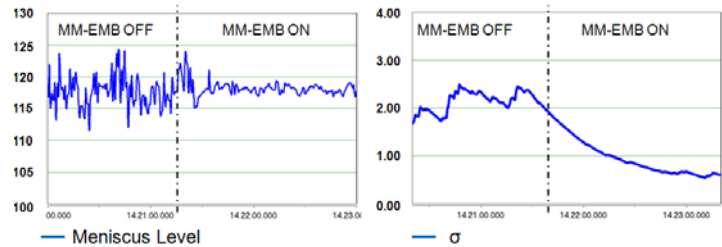
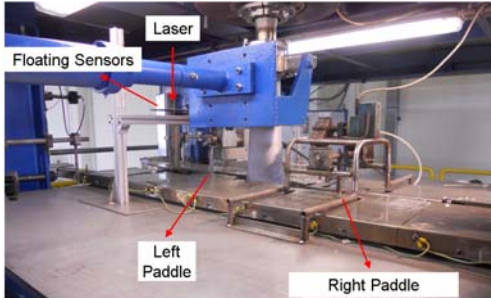


Fig. 5: Experimental Set Up including right and left paddles and a floating sensor to acquire the meniscus waviness

Fig. 6: Example of meniscus level and standard deviation of the meniscus level (σ) acquired on line during the test.

A big number of tests has been performed at different casting speeds and mold widths and with different SEN geometries. Fig. 7 & 8 show some results obtained with a mold width of 1530 mm and a casting speed of 6.2 m/min, the flow under these casting conditions being characterized by high meniscus velocity and high meniscus waviness. Fig. 7a and b show the right (blue) and left (red) meniscus flow velocity (in m/s) and the meniscus fluctuations (standard deviation σ in mm) versus time with EMB off and EMB activated. Both figures show the excellent performance of the stabilizing function that forces the very asymmetrical and unstable flow into a stable and right-left symmetrical flow. Fig. 7a shows the flow velocity decreasing at right and increasing at left versus time with EMB off, that means this shows the interesting case of an unstable flow that is about to switch from the right to the left side. Both figures show, that the response of the braking and stabilizing functions is faster (≈ 1 min) than that of the damping function ($\approx 2-3$ min). Fig. 7b shows an EMB setting for enhanced damping as compared to Fig. 7a. As a matter of fact, the stabilizing function is used permanently, but although the damping and braking functions are not really independent because the liquid flow reacts in an integrated way, it nevertheless is possible to enhance one function with respect to the other.

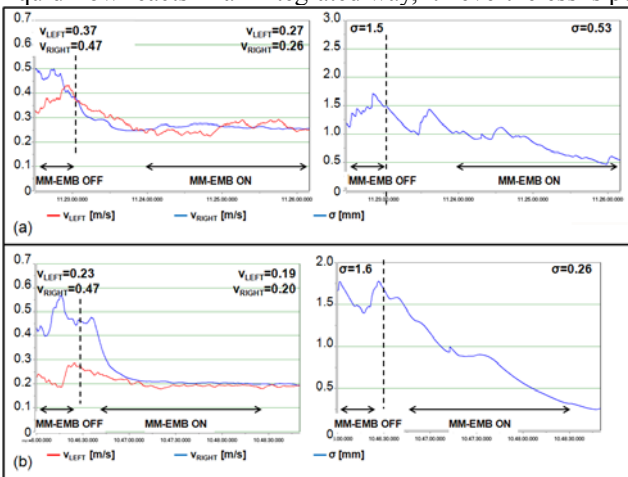


Fig. 7: Mold width 1530 and casting speed 6.2 m/min: damping and braking of two different meniscus velocities.

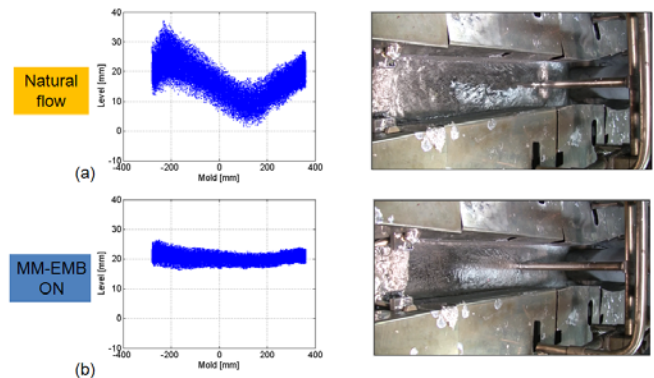


Fig. 8: Waviness Shape for mold width 1530, casting speed 6 m/min: (a) MM-EMB on (b) MM-EMB off.

Operational know how

The target of the experimental tests was not only the validation of the concept of the Multi-Mode[®] EMB, but also the development of the operating know how, i.e. the determination how to choose the EMB setting parameters (coil current of different poles) for different operation parameters of slab width and casting speed. Thanks to this unique caster

simulator we have been able to produce experimentally a huge data base of meniscus velocity (V_M) and meniscus waviness (σ) as a function of different casting speeds, mold widths, SEN geometries and EMB coil current settings. This data base is then used to represent the meniscus velocity (V_M) and the meniscus waviness (σ) in a slab width / casting speed diagram for the natural flow obtained without EMB (Fig. 9 and 10) as well as for the ‘forced’ flow obtained with a given set of EMB parameters. This data base is further used with a dedicated software in a process computer that selects automatically the appropriate EMB settings according to the actual casting speed and mold width of a thin slab caster. Thus, we can use this powerful tool to automatically control the meniscus velocity (V_M) and the meniscus waviness (σ) whatever are the casting parameters. We hence have developed not only an experimentally validated new EMB but also the operational knowhow and the automatic process control. As a result, we obtain a meniscus velocity V_M controlled within 0,1 to 0,3 m/s and a meniscus waviness σ below 0,8 mm in the validated range of caster operations of casting speed from 4 to 10 m/min and slab width from 900 to 1800 mm. Please note that the simulated casting time of this experimental work represents something like 200.000 to 300.000 t of cast steel and be sure that no steel making company in the world would accept to use its thin slab caster for such long and expensive testing.

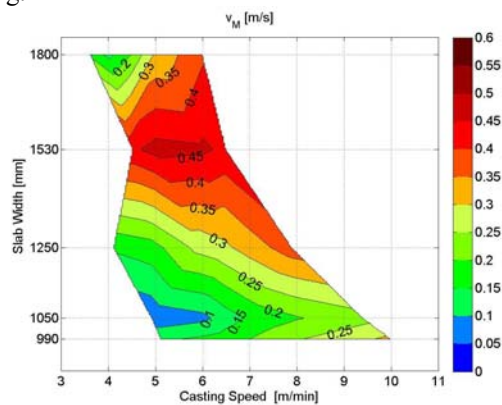


Fig. 9 : Casting speed/slab width diagram - meniscus velocity (V_M) - Natural flow

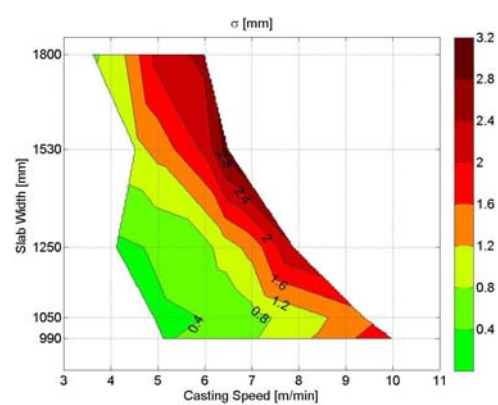


Fig. 10 : Casting speed/slab width diagram - meniscus waviness (σ) - Natural flow

Conclusion

An innovative EMB technology called Multi-Mode® EMB has been developed with distinctive functions of braking, stabilizing and damping the liquid steel in the moulds of thin slab casters. This development was possible only thanks to the combination of three mandatory activities: advanced computer simulations for concept development, experimental work with low melting metal for concept validation, full scale caster simulation for quantitative data base and automatic process control. The new Multi-Mode® EMB is able to keep the meniscus velocity (V_M) in a range of 0.1 to 0.3 m/s and the meniscus fluctuations (σ) below 0.8 mm for a caster operating in a range of casting speed 4-10 m/min and slab width 900-1800 mm.

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