Investigations on primary cooling in CC mould through the use of modeling approach

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Primary cooling and heat flux extraction in mould are key parameters in the continuous casting process: They directly control the solidification in mould and then will affect the quality of products. Solidification behaviour is at the origin of several defects or issues in the final products (Cracks, slivers, breakage/tearing...). A modeling tool, based on the use of the CFD Fluent software, was developed and applied to evaluate the effect of several parameters on solidification behavior generated in the mould: Casting speed, water cooling characteristics, copper plate material and design, slag layer thickness... The numerical results clearly show the importance of some parameters (Slag layer thickness...) on solidification behaviour while other are less or of second order (Temperature of water cooling...). This numerical tool is very useful to better understand the effect of these parameters and how to optimize them for a better control of the solidification and a better quality of products. This tool was also applied to study the origin of Ni coating cracking on copper plates observed in some ArcelorMittal plants and to propose some recommendations for solving this issue.

KEYWORDS: CC MOULD, PRIMARY COOLING, HEAT FLUX EXTRACTION, MODELLING, CFD, NUMERICAL SIMULATION, NI COATING DAMAGE;

INTRODUCTION

In continuous casting, the mold where the liquid steel starts to solidify is a critical component because it controls the initial solidification and then the quality of the products. Surface condition of the mold can also affect premature failure, then low wear life will affect the productivity of the continuous casting plant. The mold for slab products is constituted with 4 water-cooled plates (Broad and narrow faces). It is made of copper alloy which facilitates an optimal combination of thermal and mechanical properties. The inner surface of the mold is generally coated with nickel or ceramics to protect the substrate. When the casting plant is operating, an important thermal flux is transferred from the molten steel, which is in contact with the inner mold surface, to the water-cooled outer side of the mold. The mold is exposed to a high time-varying temperature combined with a high thermal gradient across the mold wall. This cyclic thermal loading promotes thermal fatigue cracks in the meniscus area, which is the most thermally stressed and strained region of the mold.

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Several numerical studies both in 2D [1,2] or in 3D [3] have been developed in the last 10 years to investigate the influence of different casting parameters on fluid flows and on the initial solidification in the mold. Some of them [1,2] are able to directly simulate the slag behavior in the mould with its infiltration between solidified shell and the mould walls. Some other are focused on the thermal behaviour of the copper plates [4,5] taking into account the precise design of the copper plates with the water-cooled channels and the coating characteristics. Several metallurgical studies [6,7,8] have been performed to determine the complex damage mechanism that occurs in the mold during its service life. A study [9] observed crack propagation through the copper substrate with a depth ranging from 0.6 mm to 5 mm. All cracks were found within the area approximately 100 to 140 mm from the top of the mold (i.e. 0 to 40 mm below the meniscus position). The mold in the meniscus zone is damaged because of a detachment of the coating material and mechanical degradation assisted by the chem-ical attack of low melting point elements on the Cu substrate which thus becomes embrittled. The coatings are affected by a thermo-mechanical degradation that reduces the mechanical properties of the deposit [10]. The inner surface of the mold undergoes high fluctuating thermal stresses, which can lead to thermal fatigue.

In order to better understand the effect of different parameters on solidification in mould and on temperature distribution on copper walls, a parametric study was launched through the use of Computational Fluid Dynam-ics. The 3D numerical tool was also applied to an industrial issue to better define the origin of mould damages occurring in some ArcelorMittal plants.

NUMERICAL MODEL

The new CFD model is used to calculate heat transfers occurring in the mold between the cooling water and the liquid steel. A 3D geometry with detailed description of water cooling channels within the copper plates is considered. The hot face of the copper plates is coated with a nickel layer. In between the copper plates and liquid steel, a slag layer is simulated. This layer is considered with a constant thickness layer. Fig 1. shows a top view of the geometry.

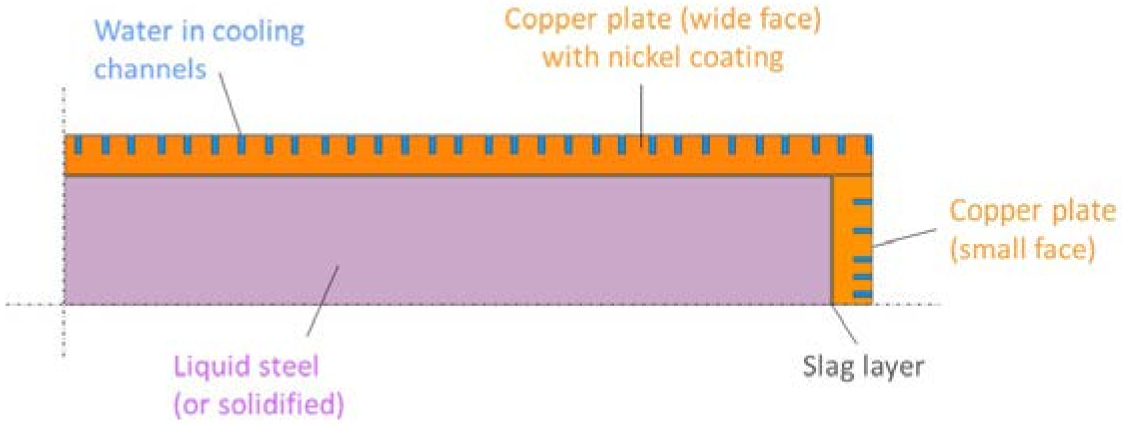


Fig.1 - Geometry used in the CFD model (top view).

Flow of liquid steel and water in the cooling channels is calculated. Heat transfers between the different regions are also calculated and solidification of liquid steel is taken into account.

The Fluent software is used to solve the following equations:

Continuity equation:

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u_i)}{\partial x_i} = 0 \qquad (1)$$

Momentum equation (Navier-Stokes):

$$\frac{\partial(\rho u_i)}{\partial t}+\frac{\partial(\rho u_i u_j)}{\partial x_j}=-\frac{\partial P}{\partial x_i}+\frac{\partial}{\partial x_j}\left[\mu_{\text{eff}}\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)\right]+\rho g+S_m \quad (2)$$

Where ui and u_j are the velocity vectors (m/s), t is the time (s), x is the coordinate corresponding to the direction i or j (i, j = x, y or z) (m), ρ is the fluid density (kg/m^3), P is the pressure (Pa), g is the gravitational acceleration (m/s^2), S_m is a momentum source term related to the influence of mushy zone on fluid flow velocities (N/m^3) and μ_{eff} is the effective viscosity (Pa.s):

$$\mu_{\text{eff}}=\mu_0+\mu_t=\mu_0+\rho C_\mu \kappa^2/\varepsilon \quad (3)$$

Where μ_0 is the molecular viscosity (Pa.s), μ_t is the turbulent viscosity (Pa.s), C_μ is the specific heat of fluid (J/kg.K), κ is the turbulent kinetic energy (m^2/s^2) and εεis the turbulent dissipation rate (m^2/s^3). The realizable (κ-ε) turbulence model is used to simulate turbulence.

Energy equation:

$$\frac{\partial}{\partial t}(\rho H)+\frac{\partial}{\partial x_i}(\rho u_i H)=-\frac{\partial}{\partial x_i}(k_{\text{eff}})\frac{\partial T}{\partial x_i}+S \quad (4)$$

Where H is the enthalpy (J/kg), k_{eff} is the effective thermal conductivity (W/m.K), T is the temperature (°K) and S is source term due to solidification (J/(m^3.s)).

We use the enthalpy-porous model for the solidification heat transfer process of liquid steel. The liquid-solid mushy zone is treated as a porous zone with a porosity equal to the liquid fraction. The momentum source term (S_m) is given as:

$$S_m=\frac{(1-\beta)^2}{(\beta^2+\varepsilon)}.A_{mush}.(u_i-u_p) \quad (5)$$

Where β is the liquid volume fraction, ε is a small number (0.001) to prevent division by zero, A_{mush} is the mushy zone constant equal to 1.10^8, and u_p is the solid velocity due to the pulling of solidified material out of the domain. Water is fed in the channels by the bottom side of the geometry with a constant temperature whereas liquid steel enters in the domain by the top face with a constant temperature and a homogeneous vertical velocity. Pressure outlet conditions are considered at outlets and no slip conditions are considered at wall surfaces. Heat transfers between the different regions is calculated by considering coupled conditions at interfaces. Water temperature increases as is goes through the channels toward the top of the mold because of the energy extracted by the liquid steel. Zero heat flux is considered at the external surfaces of the domain.

As we have considered that the liquid steel is introduced at the top of the mold with a homogeneous vertical velocity, the domain corresponds to ¼ of the mold. The mesh is made of hexahedral structured cells with very thin cells in the region of solidified shell formation geometry. The mesh size is approximately 9.5 million cells.

PARTAMETRIC STUDY BY NUMERICAL APPROACH

Table 1 summarizes the main parameters considered in the numerical simulations. Table 2 gives some details about these variable parameters with the associated case reference. The objective of these simulations was to determine the impact of different parameters on primary cooling in terms of heat flux extracted, temperature distribution on plate and solidified shell thickness at the exit of the mold.

Tab.1 - Main parameters for numerical simulation.

Mould dimensions	1750x229 mm^2
Casting speed	Variable
Superheat	25°C
Mold characteristics	Height: 0.8 m Copper plate thickness: Variable Conductivity: 377 W/m.°K
Cooling water characteristics	Temperature inlet: Variable Water flow rate in broad face: Variable Water flow rate in narrow face: 35 m3/h
Slag layer	Thickness: Variable Conductivity: 1.2 W/m.°K
Ni layer	Thickness: 3 mm Conductivity: 80 W/m.°K
$T_{liquidus}$ and $T_{solidus}$	1535°C, 1522°C

In these numerical simulations, slag layer thickness, casting speed, inlet temperature of water cooling, cooling water flow rate in broad face and thickness of the copper plate were investigated. Air gap between infiltrated slag and solidified product could have been simulated but no reliable and robust data is available. Then no simulation is proposed here. Nevertheless, the air layer plays the role of strong insulator (=Thermal resistance) and it drastically reduces the extracted heat flux in the mould.

Tab.2 - Cases simulated with values for parameters tested by numerical simulation.

Case	Slag layer thickness	Casting speed	Water cooling inlet temperature	Water cooling flow rate in broad face	Copper plate thickness
Reference	1 mm	1 m/min	40°C	250 m3/h	40 mm
1	0.5 mm	1 m/min	40°C	250 m3/h	40 mm
2	0 mm	1 m/min	40°C	250 m3/h	40 mm
3	0.8 mm	1.5 m/min	40°C	250 m3/h	40 mm
4	1 mm	1 m/min	40°C	200 m3/h	40 mm
5	1 mm	1 m/min	40°C	180 m3/h	40 mm
6	1 mm	1 m/min	30°C	250 m3/h	40 mm
7	1 mm	1 m/min	40°C	250 m3/h	30 mm

Table 3 delivers the detailed results about heat flux extracted and temperature variation (Outlet-Inlet) in narrow and broad faces and solidified shell thickness at the exit of the mold. All of these results will be de-tailed later.

Tab.3 - Cases simulated with values for parameters tested by numerical simulation.

Case	Extracted Heat flux - Broad face	Extracted Heat Flux - Narrow face	Water cooling ΔT water broad face	Water cooling ΔT water narrow face	Solidified shell Thickness
Reference	1.26 MW/m²	1.30 MW/m²	7.6°C	5.4°C	18 mm
1	1.88 MW/m²	1.96 MW/m²	11.4°C	8.1°C	24 mm
2	3.50 MW/m²	3.60 MW/m²	21.1°C	15°C	34 mm
3	1.52 MW/m²	1.59 MW/m²	9.2°C	6.6°C	15 mm
4	1.25 MW/m²	1.30 MW/m²	9.5°C	5.4°C	18 mm
5	1.25 MW/m²	1.30 MW/m²	10.5°C	5.4°C	18 mm
6	1.26 MW/m²	1.31 MW/m²	7.6°C	5.4°C	18 mm
7	1.29 MW/m²	1.31 MW/m²	7.8°C	5.2°C	18 mm

Effect of mould powder/slag properties

(Reference versus cases 1 and 2 from Table 2)

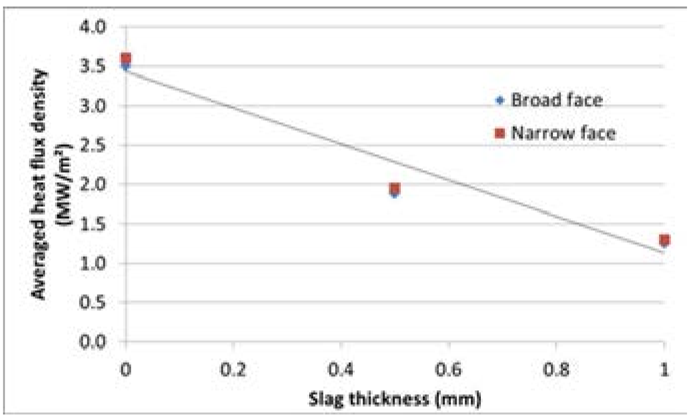
Mold powder characteristics can directly influence heat flux extracted in mould: Higher viscosity mold powders are being promoted for the purpose of lowering heat transfer. The result is a hotter slab within the mold that can affect slab-shrinkage factors and impacts lower part of the mold. Powders with lower viscosity break down faster and can inhibit proper lubrication. Too much heat transfer within the mold can result in heavy oscillation marks on the slab, which could be at the origin of surface defects like cracks. Then depending on cast grades, different mold powder properties are used.

In this study we focus on the effect of the slag layer thickness infiltrated between the solidified product and the mould walls.

As expected, the slag layer plays the role of insulator (=Thermal resistance) between hot liquid steel and cold cooling water by:

- Decreasing heat flux in mould and shell thickness at mould exit with an increase of slag layer thickness, almost linear (See Figure 2)
- Decreasing mold surface temperature with an increase of slag layer thickness

When no slag is considered in the simulation, very high copper surface temperature (>900°C) is reached which is very detrimental for copper plates properties.



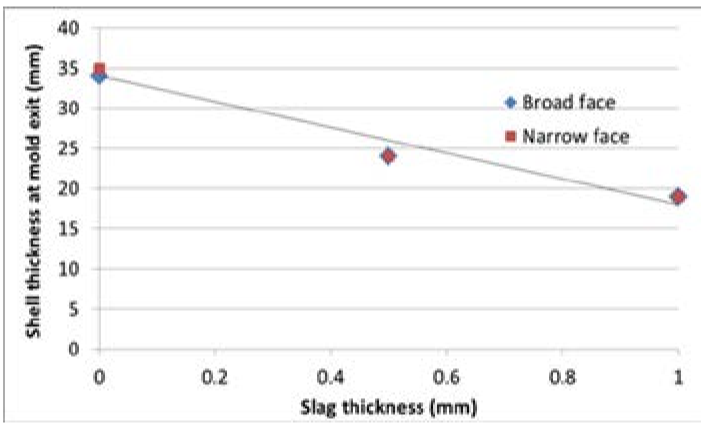


Fig.2 - Effect of infiltrated slag thickness on heat flux extraction (Left) and on solidified shell thickness (Right).

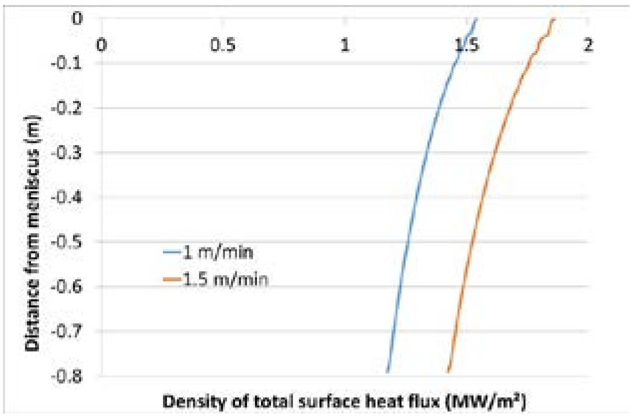
Effect of casting speed

(Reference versus case 3 from Table 2)

For slab CC machine, casting speed can vary between 0 (When stoppage occurs) and 2m/min (Max value in some ArcelorMittal plants). Then heat transfer in mould could be greatly affected by this parameter.

Moreover, it exists some correlations between slag layer infiltrated and casting speed [11]. In our simulations, the slag layer thickness is fixed to a constant value. In these new simulations about casting speed effect the thickness was adjusted in order to agree with the industrial measurements of the heat flux extracted in the mould for the same casting conditions. In these casting conditions, the slag layer thickness was reduced from 1 mm to 0.8 mm when casting speed was increased from 1 to 1.5 m/min. This value is quite in good agreement with values found in literature.

Then according to the results of this new simulation, an increase of the casting speed induces and increase of the heat flux extracted in the mould but also a decrease of the solidified shell thickness at the exit of the mould (See Figure 3).



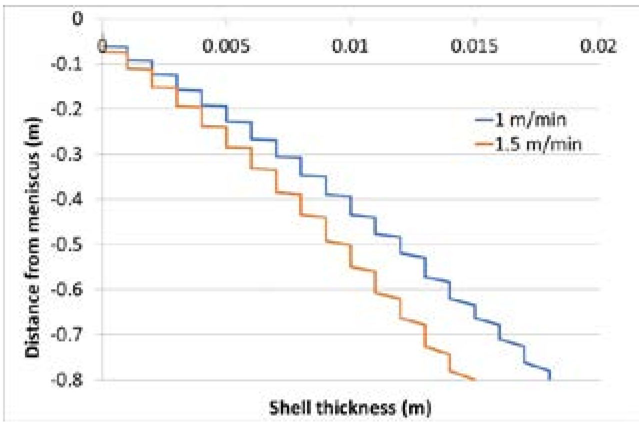


Fig.3 - Effect of casting speed on extracted heat flux (Left) and on solidified shell thickness (Right) along the mould height on broad face.

Effect of cooling water characteristics

In [1] the 2D numerical results show no effect of the water flow rate on the solidified shell thickness at mold exit, only a weak influence is observed close to the meniscus. In [12], the experimental results show that a decrease of the water flow rate in broad face induces smaller hook depth.

In our simulations, we teste 2 different parameters concerning primary cooling water: The flow rate through the broad face and the inlet temperature.

Water flow rate

(Reference versus cases 4 and 5 from Table 2)

Figures 4 and 5 show that a decrease of water flow rate from 250 m^3/h to 180 m^3/h leads to:

- Higher water temperature increase (From 7.6°C to 10.5°C),
- Slightly lower heat flux extracted (From 1.257 to 1.248 MW/m^2) with variation almost linear,
- A similar shape of heat flux profile along mold height,
- A direct impact on mold surface temperature level but no impact on temperature distribution,
- No effect on solidified shell thickness at mold exit.

Then, due to change in temperature level, especially at meniscus location, we can imagine that this parameter can affect solidified structures and then impact surface quality of the products (Cracks…).

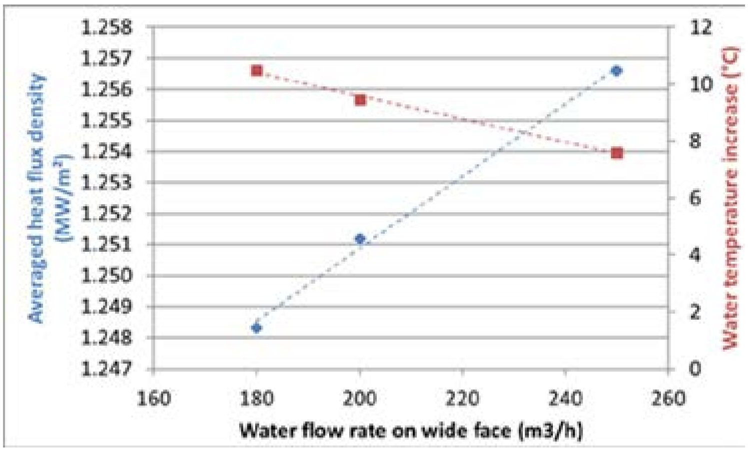


Fig.4 - Effect of cooling water flow rate on extracted heat flux and on water temperature increase.

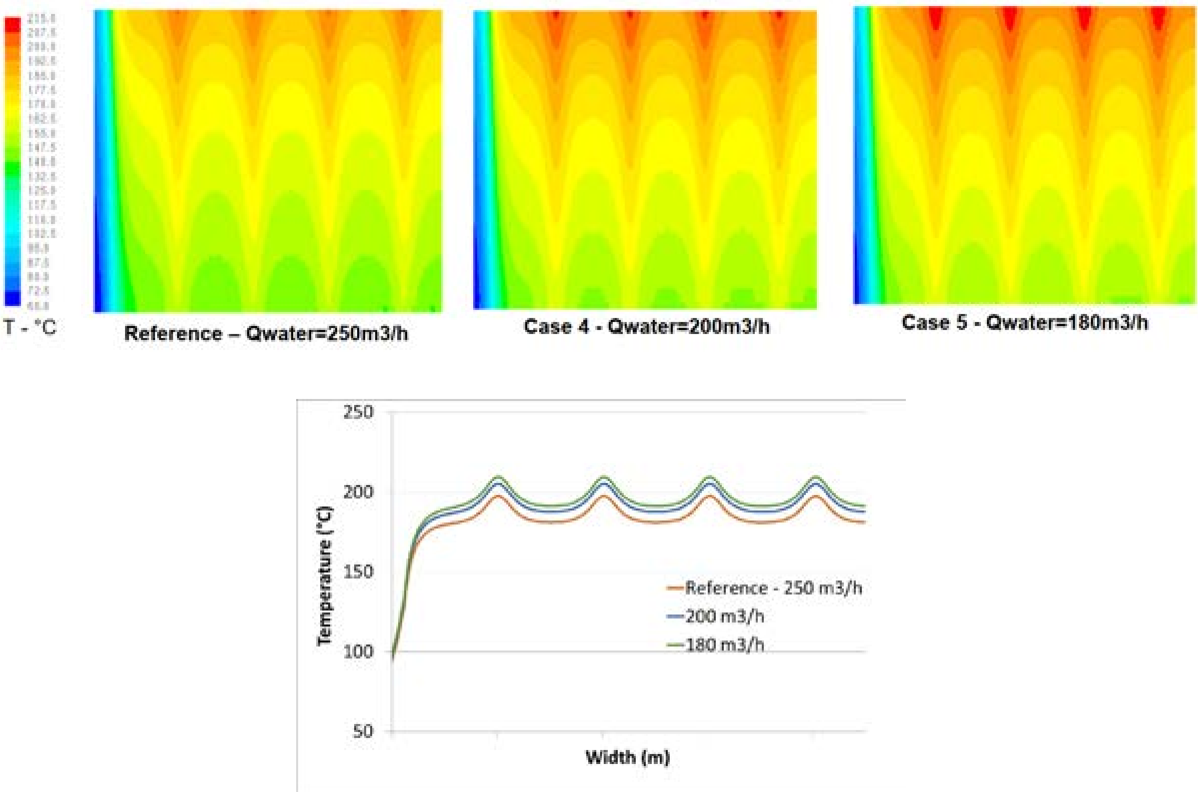


Fig.5 - Effect of cooling water flow rate on broad face temperature distribution (Up) and temperature profile along the mould width (Down).

Water inlet temperature

(Reference versus case 6 from Table 2)

In that configuration, by decreasing the inlet temperature of the water cooling, the numerical results illustrated on Figure 6 and in Table 3 show that there is:

- No real effect on heat flux extracted in mould,
- No effect on solidified shell thickness at mould exit,
- No effect on water temperature at outlet,
- An effect with a decrease of the temperature distribution on mold surface especially at meniscus location.

Then, due to change in temperature distribution, especially at meniscus location, we can imagine that this parameter can affect solidified structures and then impact surface quality of the products (Cracks). From time to time, some plants mention seasonal effects on products quality. Could the seasons have an impact on inlet temperature of water cooling and then affecting thermal behavior in the mold?

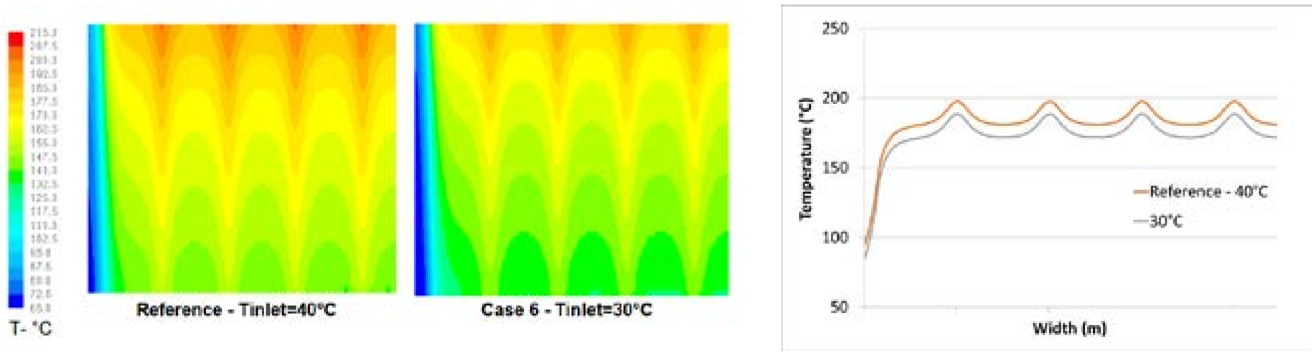


Fig.6 -Effect of inlet cooling water temperature on broad face temperature distribution (Left) and profile along the mould width (Right).

Effect of copper plate thickness

(Reference versus case 7 from Table 2)

Decreasing copper plate thickness from 40 mm to 30 mm changes temperature distribution and heat trans-fers in the mould. According to Figure 7 and Table 3, with thinner plates, we observe:

- Lower mold face temperature: Higher efficiency of water cooling
- Higher extracted heat flux but with limited effect,
- No impact on solidified shell thickness at mould exit.

Then, clearly it appears with these results that the heat transfers in the mould will be affected by this parameter throughout its lifetime. Wear of the plates occurs sequence after sequence and plates are remachined regu-larly. Therefore, without any specific correction, the heat transfers in the mould will change continuously and should affect quality of products. Special attention has to be paid to this parameter especially when critical limits are reached.

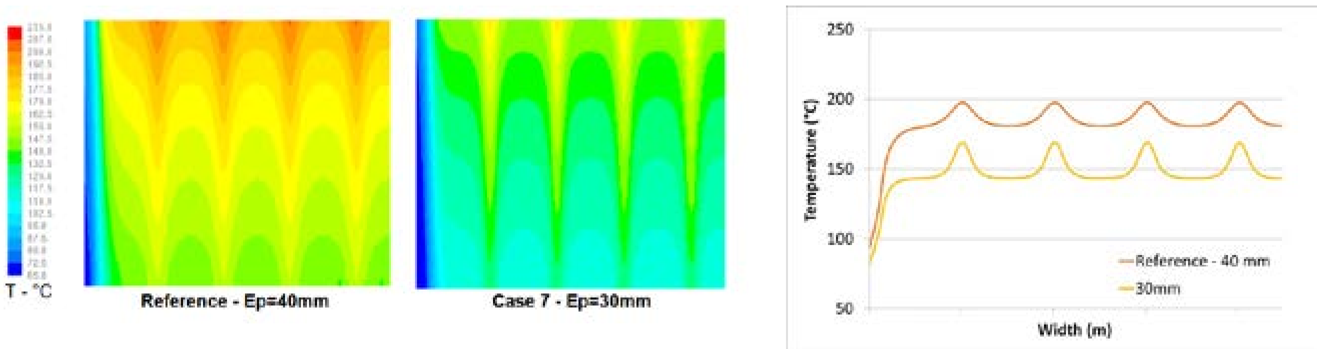


Fig.7 - Effect of copper broad face thickness on broad face temperature distribution (Left) and along the mould width (Right).

Other parameters affecting heat transfers in mould

Copper materials have a relatively low hardness and thus low resistance to abrasive wear. For this reason, a high degree of wear can occur in the lower part of the mould where the strand shell causes increased levels of stress. To improve the service life of moulds, dedicated coatin-gs (Ni, Cr, ceramics...) can be applied. When it concerns coatings for mould plates, a distinction has to be drawn between coatings for metallurgical protec-tion to improve the surface quality of the products (Prevention of cracks), and anti-wear coatings to improve resistance to abrasion. In this parametric study, this parameter was not considered to change and was fixed to a constant value. However, this parameter plays the role of another thermal resistance and it will directly affect the heat transfers in the mould.

Finally, the copper material itself and its nature (CuAg versus CuCrZr for example) can affect the heat transfers in the mould. Due to properties modification, especially the thermal conductivity, the cooling efficiency will be affected and then the mould temperature itself will be modified. In this parametric study, this property was not considered to change and was fixed to a constant value.

Based on this parametric study, a lot of parameters affect heat transfers in mould and then the initial solidifi-cation. Such a numerical tool is very useful to evaluate and adjust process parameters for casting good prod-ucts quality and reduce incidents during casting which could cause some damages to the mould.

INDUSTRIAL APPLICATION: Copper plates damage in CC mould

From time to time, some ArcelorMittal plants face some issues with copper plates damage due to cracking of coating.

Industrial issue

High temperatures directly influence the base copper and coating performance. The mechanical properties of copper, nickel-base products, can be damaged during high-temperature casting. Cracking of a coating in the meniscus region caused by mechanical breakdown will subsequently deteriorate the copper-base material. An illustration of such a phenomenon is presented on Figure 8.

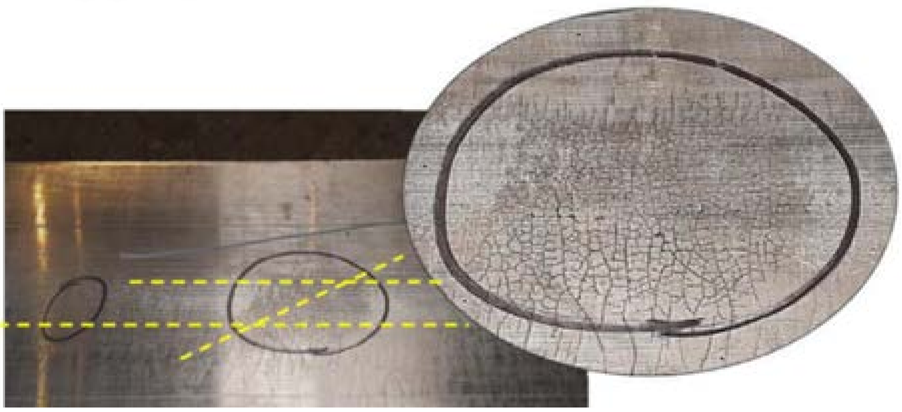


Fig.6 -Ni coating damage on broad face.

Then, in order to better understand the situation in the plant some investigations were carried out:

(1) Numerical simulation to determine the possible origin of the damage in terms of heat transfer in the mould

(2) Industrial checking of water quality and Ni coating behavior (Before and after casting)

Investigations by numerical simulation by R&D and in the plant

The ArcelorMittal plant concerned by this issue uses 2 different mold designs for casting (Different designs of co-

oling channels) and they observed that one mold is more affected by this issue than the other. This issue occurred in summer time with high weather temperature and just after maintenance operation at cooling towers.
The numerical results applied for these 2 configurations (D1 and D2) are illustrated in Figure 9. They clearly highlight that mold D1 presents more heterogeneous temperatures especially close to meniscus location, where the damage is observed, with higher temperature level (At least 30°C more).
These results are obtained in standard casting conditions (=Normal conditions). We can suppose that in degraded conditions (With higher inlet temperature, with reduced water flow rate...) the temperature heterogeneity and the temperature level could be exaggerated.

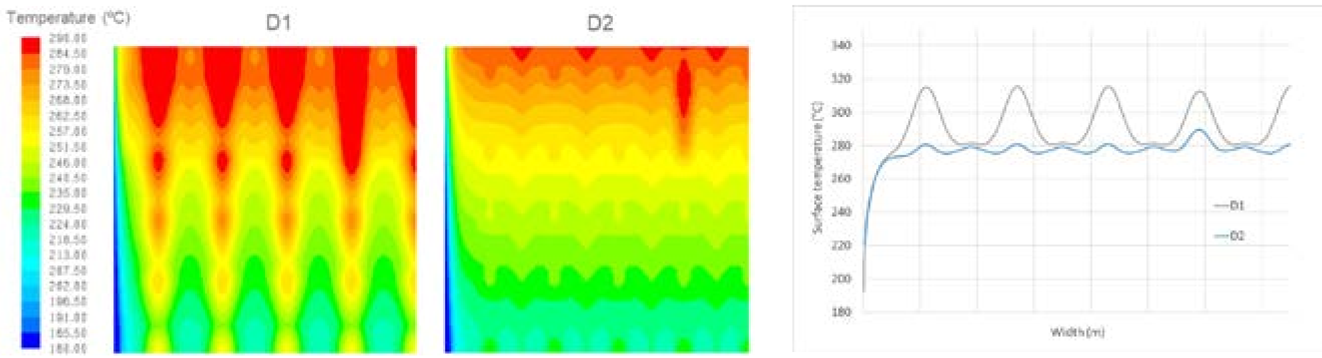


Fig.9 - Effect of plate design on broad face temperature (Left) and on temperature profile along width (Right) depending on plate design.

These numerical results are interesting, but they are not enough to explain the issue met with the mould coating damage.

Then, at the same time, the plant started some internal investigations to better understand the situation.

- During a maintenance operation of the cooling boxes of the mould, the operators discovered important corrosion inside the boxes with some channels blocked by corrosion. It means that the cooling efficiency by water is weaker than in normal conditions.
- During machining of plates, the operators measured the presence of Zn at high level in plates in Ni coating area. It means that Zn penetrates the grain and further expand the cracks through the coating and copper substrate.

Explanations and recommendations

Extremely high temperature on the hot face of the Cu mold at meniscus area is found the cause of the mold heavy erosion problem. The corrosion of cooling boxes has affected the water flow rate and has significantly reduced water cooling efficiency. It directly causes the hot face temperature of the Cu mold to rise to an unacceptable level. This high temperature situation accelerates the failure of Ni coating and the erosion of Cu by presence of zinc in the steel. For operations where scrap materials are used in the melt, the result can lead to zinc concentrations that penetrate into the grain and further expand the cracks through the coating and copper substrate. The mold design has amplified this phenomenon but is not at the origin of the issue.
Corrective actions were proposed, and everything comes back in order...

CONCLUSION

Continuous casting is a very complex process depending on many parameters. This numerical investigation based on the use of a 3D CFD numerical tool shows that several parameters directly affect and control heat transfers in the mould and initial solidification which is a key element for products quality. Numerical tool as well as online sensors will be more and more useful to better control and optimize the CC process in the future.

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