NUMERICAL MODELS AND THEIR INDISPENSABILITY FOR FLEXIBLE CONTROL OF CONTINUOUS STEEL CASTING

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Abstract

Outdated machine for continuous casting of steel (CCM) has often fail to meet the requirements for production of the desired high quality carbon or stainless steel blank. Their control system acts as a so-called Black Box System, which provides operators the possibility of the system as needed to adjust and tune in order to achieve the required quality of steel produced. During the reconstruction of the caster is especially suitable to modify the secondary cooling, and slab CCM own rollways controlled cone possibly complemented well pronounced soft reduction. The necessary hardware modifications CCM cannot be designed without major upgrades the software control system based on the formation of new numerical models and their application to reduce of surface cracks and corners and central cavities or other defects. It was therefore developed a series of numerical models in the form of modules, control modules and data visualization modules. Based on the model of the temperature field of the strand. The inclusion of modules in the control system CCM, which depends on the capabilities of the caster and customer requirements, can be built into the server embeddable the second levels of management. This server communicates via OPC protocol with superiors and subordinates systems. It also includes off-line simulator that allows you to test and simulate different cooling strategy and settings for different steel grades. The flexibility of such a solution is presented for converting the caster with nine to thirteen engine cooling zones and optimizing the secondary cooling supported by on-line numerical optimization, the current temperature field slab. It is also demonstrated by the inclusion of a modular system management system CCM.

Keywords: Continuous casting, secondary cooling control, soft reduction

1. INTRODUCTION

The development of radial slab caster (CCM for the first slab width of 1500 mm, from 1962 has come a long way [1]. In **Fig. 1**, **2** and **3** are examples of radial slab caster, in all instances it is a machine for the final slab thickness slabs of 200 mm and a variable width of between 800-1600 mm for casting speed max. 1.6 m/min at least three generations. The length of the caster (CCM) from the upper edge of the mold after the cutting torch in all cases is approximately 26 meters. **Fig. 1** is operationally oldest machine **Type A**, which only has 9 independent cooling zones. **Fig. 2** shows caster modernization, where the number of cooling zones 13 further extended to **Type B**. In both cases it is a variant having a curved mold and reduction of profile fixed arc. **Fig. 3** shows a modern variant of the machine 17 cooling zones that has a straight mold and is constructed of curved sections, as well as **Type C**. Another trend is the use of slab caster at air-mist nozzles instead of water nozzles, as is the case with the machine in **Fig. 3**. Increasing cooling zones in conjunction with air-mist nozzles allows much more accurately adjust and control the secondary cooling for achieving optimum surface temperatures along the entire caster, thus to increase the surface quality of the preform [2]. It is possible to offset the cooling effect uniformly along the whole machine and even in dynamic changes the casting speed. Optimal adjustment of the secondary cooling can eliminate the occurrence of internal defects, but the decisive influence ends, the position Mushy zone and setting the reduction in the individual segments. Therefore, the trend is to equip the machine hydraulically adjustable segments which during casting are reduced by the profile in place of the end-of Mushy called soft-reduction **Fig. 4**. Modern CCM already have so many interconnected controllable variables that are not enough already with the management at 1st Level (PLC) and therefore it is necessary to shift the main control algorithms to 2nd Level. The new control algorithms are based on mathematical models and allow us to regulate and watch over the links between different control variables [3].

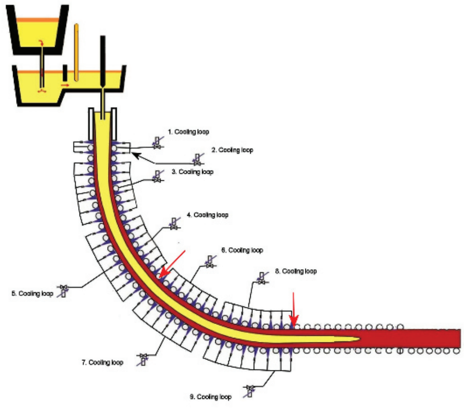


Fig. 1 Diagram 9 cooling zones slab caster (Type A)

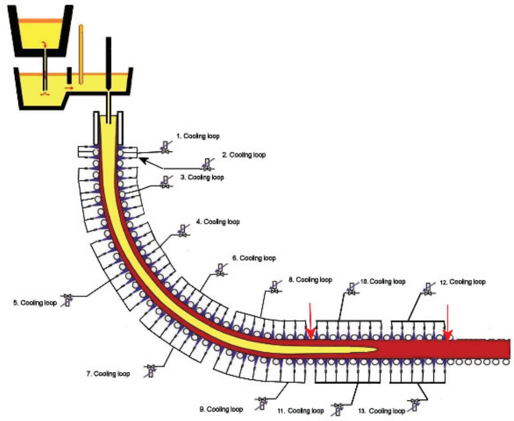


Fig. 2 Diagram 13 cooling zones slab caster (Type B)

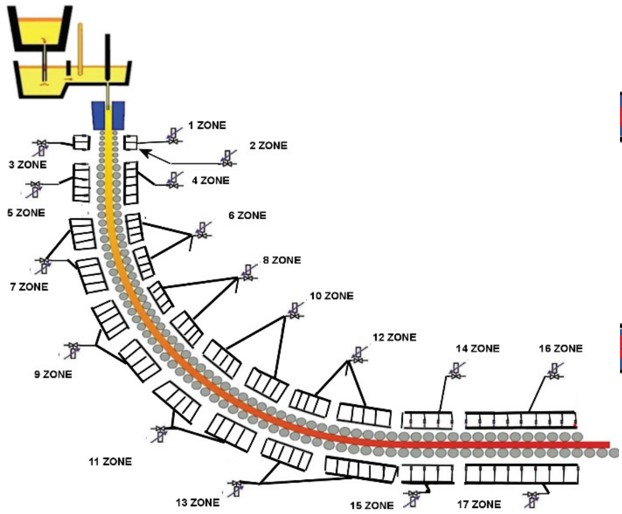


Fig. 3 Diagram 17 cooling zones slab caster (Type C)

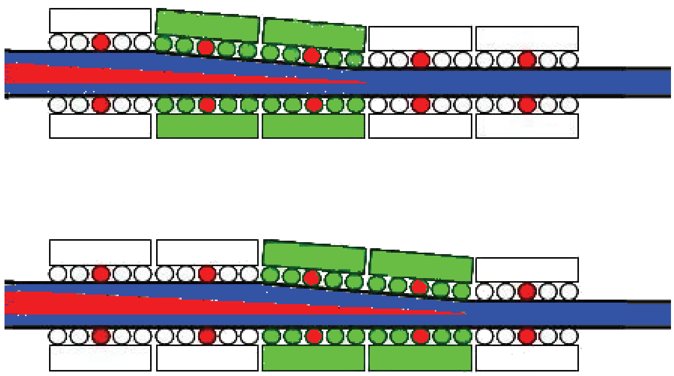


Fig. 4 How it works softreduction

2. DYNAMIC SOLIDIFICATION MODEL

The basic model for the smooth management of the second level of solidification is a 3D dynamic model solidification and cooling of the slab can work as both online and offline simulator. The numerical model takes into account the temperature field of the entire slab (from the meniscus of the level of the melt in the mould to the cutting torch) using a 3D mesh containing more than a million nodal points. The solidification and cooling of a concast slab is a global problem of 3D transient heat and mass transfer. If heat conduction within the heat transfer in this system is decisive, the process is described by the Fourier-Kirchhoff equation. It describes the temperature field of the solidifying slab in all three of its states: at the temperatures above the liquidus (i.e. the melt), within the interval between the liquidus and solidus (i.e. in the mushy zone) and at the temperatures below the solidus (i.e. the solid state). In order to solve these it is convenient to use the explicit numerical method of control volumes. Numerical simulation of the release of latent heats of phase or structural changes is carried out by introducing the enthalpy function dependent on temperature T, preferably in the form of enthalpy related to unit volume H_v. The latent heats are contained here. After the automated generation of the mesh (pre-processing) ties on the entry of the thermophysical material properties of the investigated system, including their dependence on temperature. They are namely the heat conductivity k, the specific heat capacity

c and density ρ of the cast steel. The temperature distribution in the slabs described by the enthalpy balance equation [4]. The simplified equation (1), suitable for application on radial-casters with a great radius, where only the speed (of the movement of the slab) component w in the z-direction is considered, is:

$$\frac{\partial H_V}{\partial t}+\frac{\partial}{\partial z}\left(\rho w_z H_V\right)=k\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right) \tag{1}$$

Volume enthalpy H_V as a thermodynamic function of temperature must be known for each specific steel. It is dependent on the composition of the steel and on the rate of cooling. A unknown enthalpy of the general nodal point of the slab in the next time step ($\tau+\Delta\tau$) is expressed by the explicit formula:

$$H_{v_{i,j,k}}^{(\tau+\Delta\tau)}=H_{v_{i,j,k}}^{(\tau)}+\left(Qz1_{i,j}+Qz_{i,j}+Qy1_i+Qy_i+Qx1+Qx\right)\frac{\Delta\tau}{\Delta x\Delta y\Delta z} \tag{2}$$

The heat flow through the general nodal point *(i,j,k)* in the z-direction is described by the following equations

$$Qz_{i,j}=k\frac{A_z}{\Delta z}(T_{i,j,k+1}^{(\tau)}-T_{i,j,k}^{(\tau)})-A_z w_z H_{v_{i,j,k}}^{(\tau)} \tag{3}$$

The initial condition for solving is the setting of the initial temperature in individual points of the mesh. A suitable value is the highest possible temperature, i.e. the casting temperature. The boundary conditions are in different places and different systems are described by equations 4a and 4e.

1. $T=T_{cast}$ at the meniscus (4a)

2. $-k\frac{\partial T}{\partial n}=0$ at the plane of symmetry (4b)

3. $-k\frac{\partial T}{\partial n}=a-b\sqrt{\frac{L_{Mould}}{w_z}}$ in the mold (4c)

4. $-k\frac{\partial T}{\partial n}=\left[h_{tc}+\sigma_o\varepsilon\left(T_{Surface}^2+T_{Amb}^2\right)\left(T_{Surface}+T_{Amb}\right)\right]\left(T_{Surface}-T_{Amb}\right)$ in the secondary and terciary -cooling zone (4d)

5. $-k\frac{\partial T}{\partial n}=11513.7T_{Surface}^{0.76}w_z^{-0.2}(2\theta)^{-0.16}$ beneath the support rollers [5] (4e)

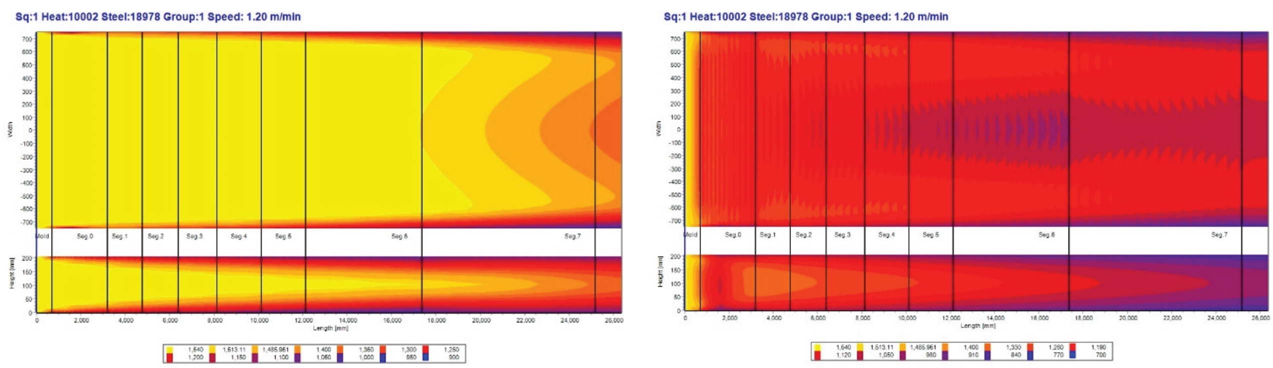
3. THE SERVER DYNAMIC SOLIDIFICATION MODEL

Due to the nature of software solutions developed a dynamic model for solidification, which is designed as a client server application where the client can be classic HMI application or Web browser. Therefore, in this case very much depends on the server hardware. Software model for achieving optimized for use on hard-ware server. Server performance should be chosen according to the demands of the models and parameters of continuous casting. Configuration software depends upon the number of streams of continuous casting, whether only calculated temperature field is regulated or secondary cooling and softreduction [9, 10]. Furthermore, if the server also includes off-line simulator, optimizer [8], and many other parameters. Basic configuration RACK server performance dual-processor server Intel Xeon processors with six cores running under MS Windows Server. For higher demands should be equipped with the appropriate server accelerator card either using GPGPU NVIDIA Tesla and CUDA uses a software technology [11] or card INTEL XEON-Phi using technology OpenCL. The example thus scalable server from SuperMicro is shown in **Fig. 5** [12].

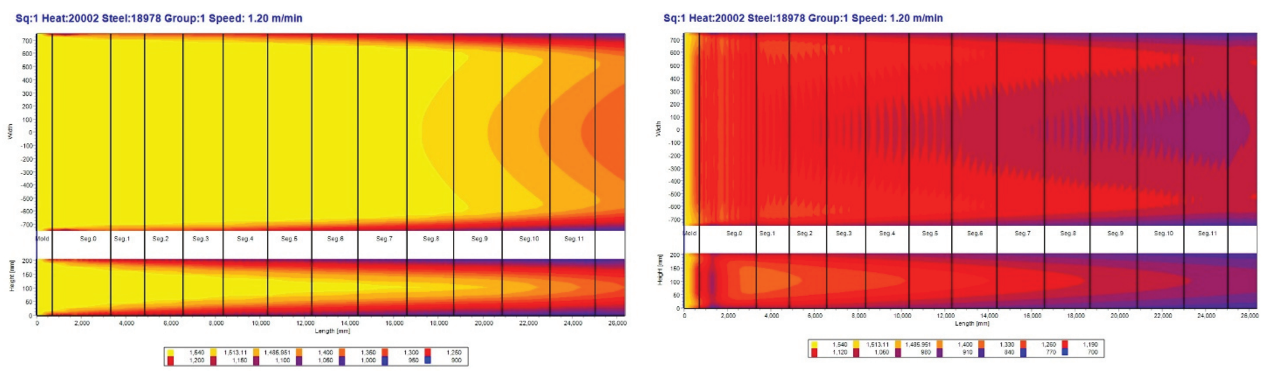
Fig. 5 Example of server hardware and computational accelerator cards [12]

4. EXAMPLES OF RESULTS OF THE DYNAMIC MODEL OF SOLIDIFICATION

To view the final computed temperature field as a basis for decisions operator or technologist been proposed compact views. All results are for the same conditions i.e. slabs cast profile 1500x200 mm made of steel grade 1.8978 (L555MB) with a casting temperature in a tundish 1540 °C at a constant casting speed of 1.2 m/min. Cooling only is configured optimally for the type of continuous casting and cast steel. The resulting temperature field is shown for three different machines presented in **Fig. 1**, **2** and **3**. **Fig. 6** is a view in the color contour in central sections, this view gives us a clear idea of the position and shape of mushy zone or when called metallurgy length.



a) Caster Type A



b) Caster Type B

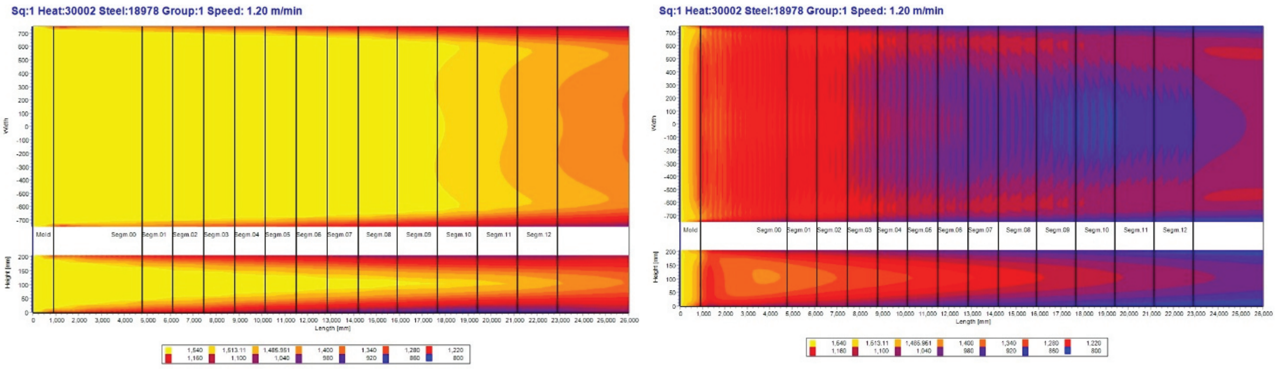
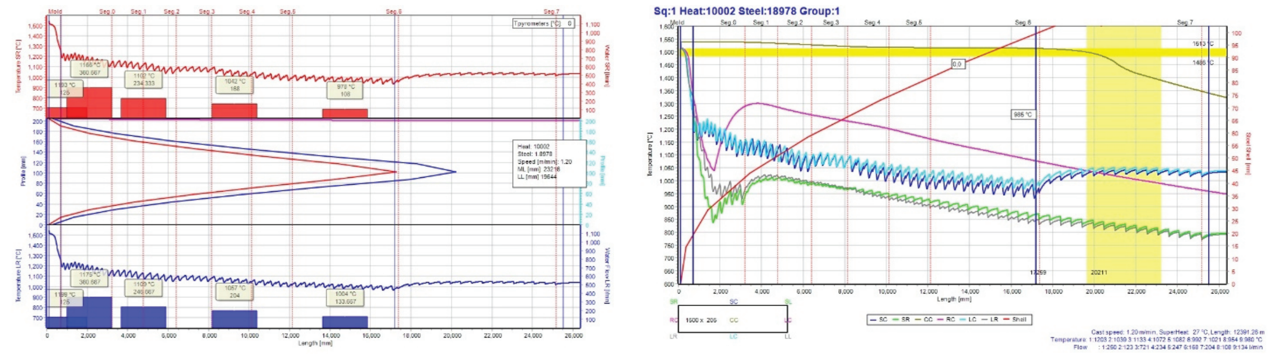
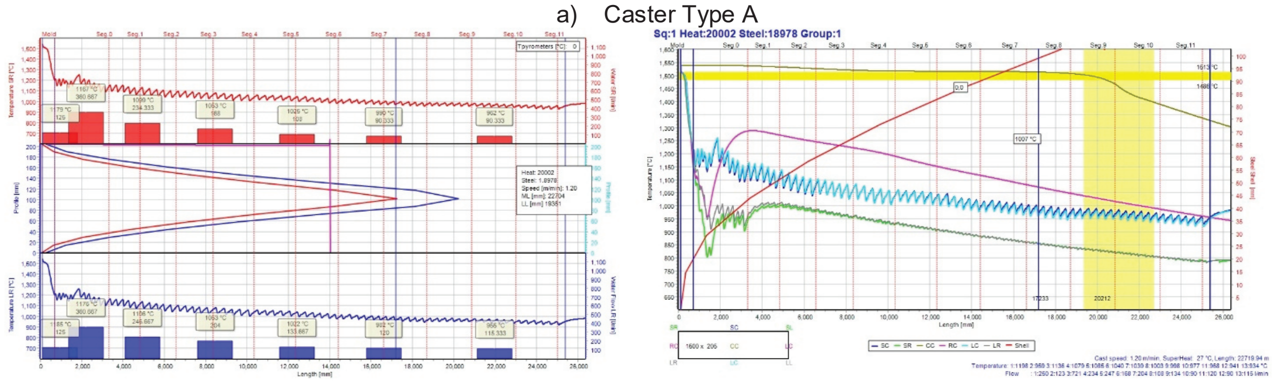


Fig. 6 Temperature field in central cross section and top (small radius) surface

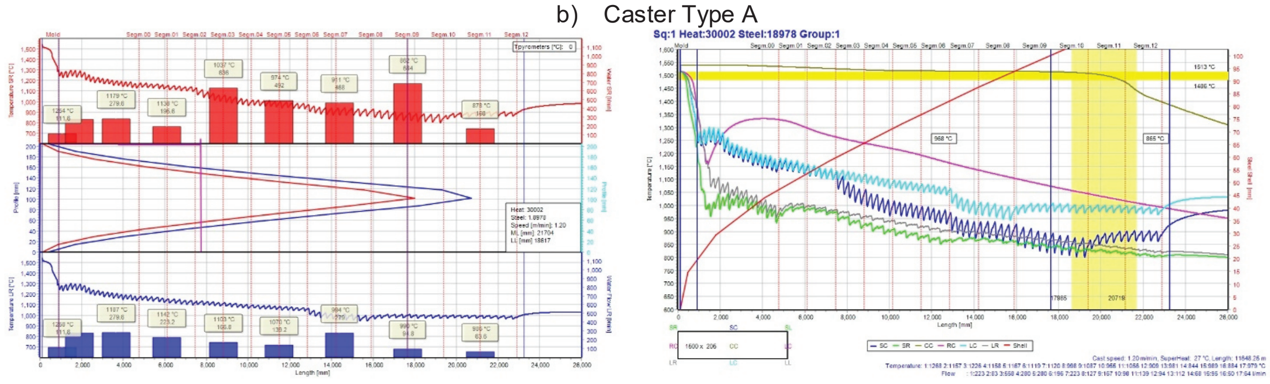
Fig. 6 is the same for the cases shown in the right column of the surface temperature to a small radius, or if the top surface and the right side, this display can be switched to the lower surface and the left side. These views are useful for quick information when changing temperature field especially in the steady state, conversely, for detailed tracking of the secondary cooling functions and softreduction are suitable plots of **Fig. 7**.



a) Caster Type A



b) Caster Type A



c) Caster Type C

Fig. 7 Temperature history along whole caster

In the right column in **Fig. 7** is a combined graph showing a cone in the middle, or if the actual position Mushy zone control functions softreduction and in the upper part, the course of the surface temperature on the upper surface, including the actual water flow cooling zones and the desired surface temperature. At the bottom of the graph is the same graph for the bottom surface. In the right part of **Fig. 7** is a graph of the classical temperature along the entire machine at selected points and the waveform profile of the shell thickness in the central section.

5. CONCLUSION

Hardware modifications necessary CCM, especially its cooling zones, cannot be designed without a fundamental modernization of the control system software level two, which is mainly based on a dynamic model of solidification it was therefore developed a series of numerical submodels in the form of modules, control modules and display modules. Based on the original numerical model of the temperature field, addressing the 3D transient heat and mass transfer in the system slab-mold respectively slab-surrounding. The model is equipped with an interactive graphical user interface for automatic generation networks, enabling easy change of cast profile both in casting and before the start of the sequence and to evaluate the results. Off-line version of the model (off-line simulator) can perform parametric studies, ie. to analyze the effect of various initial and boundary conditions to achieve optimal temperature distribution in the slab to enhance its quality.

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