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Control of Billet Temperature Field by the Secondary Cooling in Continuous Casting of Steel

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***Abstract*—The paper presents simulation study on control of temperature field of steel billet during continuous casting. The cooling of steel billet is controlled with secondary cooling zone – a set of water jets divided into independent subzones. The temperature field evolution in time and space is described by non-linear partial differential equation. The solution of this equation is obtained numerically, using specialized finite element software ProCAST. Lumped-input and distributed-parameter-output system (LDS) is introduced, with the inputs being cooling water flow rates and the temperature field being the system's distributed output. Control synthesis in the system's feedback is solved in space and time direction. To represent the temperature field during setpoint changes a co-simulation interface was added to the DPS Blockset (Third-Party software product of The MathWorks). The interface block enables you to couple a finite element simulation in ProCAST and control scheme in Simulink. This feature brings you the full power of Simulink to extend the capabilities of finite element simulation.**

Keywords*—continuous casting; steel billet; temperature field; control; lumped-input and distributed-output system; distributed parameter system; co-simulation

I. INTRODUCTION

Continuous casting (CC) of steel is one of the fundamental metallurgical technologies; in 2011, continuously-cast products accounted for 94 % of world's steel production [1]. This sophisticated and highly-refined technology, Fig. 1, aims to reach effective production of high-quality products while at the same time taking the challenge of minimizing energy consumption and environmental burden.

The CC technology can be briefly described as follows: the liquid metal is poured from the ladle (1) into the tundish (2) from where it is transferred in a controlled manner through submerged entry nozzle (3) into the water-cooled copper mould (4), being the primary cooling zone of the casting machine. At the mould walls, solidified shell of the casting strand is being formed while the casting core remains liquid (5). The strand is supported by rollers, which support the solidified shell of the strand against the ferrostatic pressure. To increase the rate of solidification, surface of the casting strand is sprayed with cooling water as it passes through the spray chamber, being the secondary cooling zone of the casting machine (6). This cooling zone is usually divided into several independent sections (6.1, … , 6.*i*, … , 6.*n*), using various cooling nozzle arrangements. Final solidification and straightening take place after the strand has exited the secondary cooling zone (7). Being thoroughly solidified and straightened, the strand is cut to lengths and prepared for further processing (8). Production quality is considerably influenced by temperature variations during cooling in secondary cooling zone.

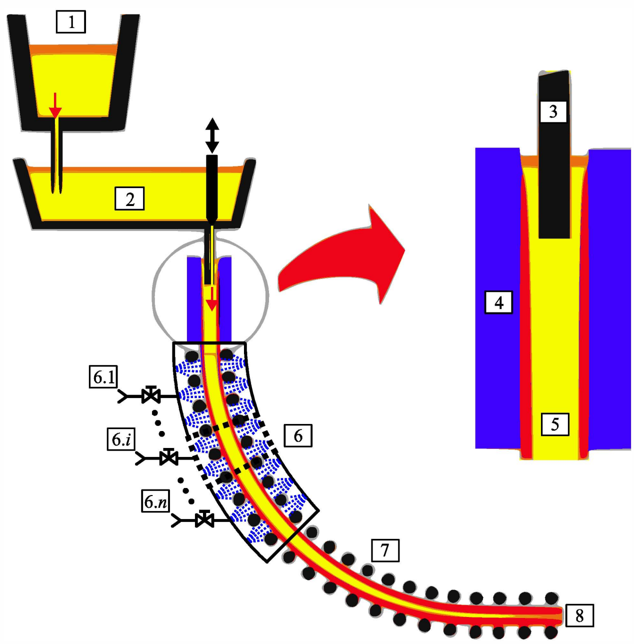

Fig. 1. Continuous casting technology

This presents control challenges for the team of researchers all over the world [2], [3], [4]. Today's great advances in computer power enable engineers to fully exploit capabilities of virtual engineering environments in various engineering areas [5]. For heavy industry in particular, ProCAST simulation software has been developed for shape as well as continuous casting technology, using finite element method for solution of nonlinear partial differential equations (PDE) that describe physical processes occurring in casting.

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On the other hand, systems and control theory considers PDE-governed systems as distributed parameter systems [6]. For our purpose, DPS dynamical characteristics of the strand secondary cooling have been obtained in ProCAST while the control synthesis was performed using engineering methods of DPS control [7], [8], [9], and [10]. Results obtained take form of a co-simulation of two software packages working in parallel: for dynamics modelling, ProCAST served the purpose whereas for control, Distributed Parameter Systems Blockset for MATLAB & Simulink (DPS Blockset) a Third-Party MathWorks product was utilized [11].

The majority of results presented here stems from cooperation of Slovak University of Technology in Bratislava (Faculty of Mechanical Engineering, Centre for Control of Distributed Parameter Systems) and Železiarne Podbrezová, Inc. (Project ARPKONTI – Adaptive control of continuous casting processes of steel in Železiarne Podbrezová, Inc. as distributed parameter systems).

II. Secondary Cooling Zone As a Lumped Input And Distributed-Output System

A typical Steel CC process is shown in Fig. 1. The secondary cooling is very important during this process and maintaining a correct temperature field is crucial to the quality of the product. In Fig. 2 it can be clearly seen that various roll and nozzle arrangements render the typical temperature patterns on the strand surface.

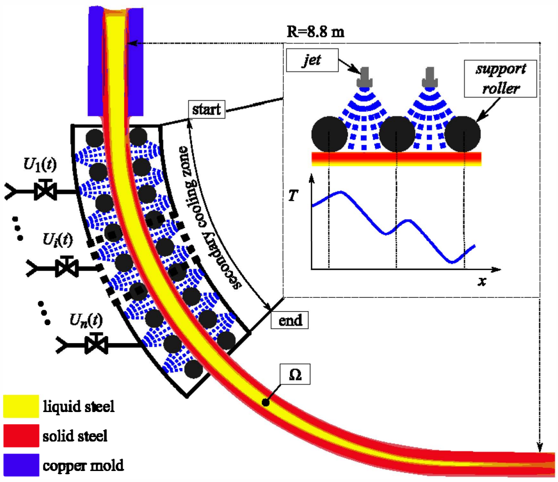

Fig. 2. Temperature profile of the strand surface in secondary cooling zone.

Cooling water nozzles are arranged into independent sections with individually controlled flow rates $\{U_i(t)\}_{i=1,n}$, Fig. 3.

In general, the CC secondary cooling process is governed by a nonlinear PDE relating the cooling rate $\dot{Q}_Y(x,y,z,t)$ and temperature field of the strand $Y(x,y,z,t)$

$$\rho\left(c_p - L\frac{\partial fs}{\partial Y}\right)\left(\frac{\partial Y}{\partial t}+\nabla Y\cdot \mathbf{v}\right)-\nabla\cdot\left(\lambda\nabla Y\right)=\dot{Q}_Y, \qquad (1)$$

where $\mathbf{v}$ is the casting speed, L latent heat of fusion, ρ density, λ thermal conductivity, c_p heat capacity, fs fraction of solid, the latter four being temperature dependent.

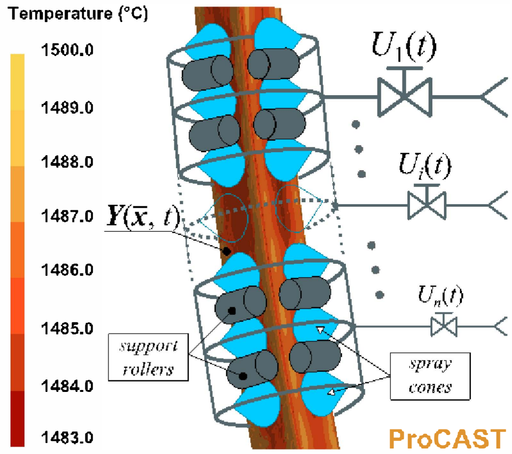

Fig. 3. Dynamical system: relation between water flow rates and temperature field of the strand. $\boldsymbol{Y}(\bar{\boldsymbol{x}},t)=\boldsymbol{Y}(x,y,z,t)$ is the system's output, the strand temperature field.

This in general represents a distributed-input and distributed-parameter-output system (DDS).

Fig. 4. Distributed-input and distributed-parameter-output system.

By connecting the nozzle spray characteristics $\{GU_i\}_{i=1...n}$ and blocks representing flow control valves and connecting piping dynamics $\{SA_i\}_{i=1...n}$ we obtain a lumped-input and distributed-parameter-output system (LDS)

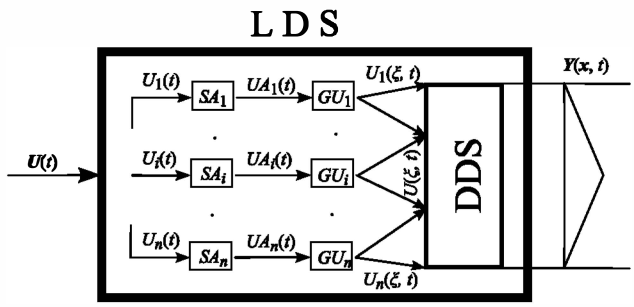

Fig. 5. Lumped-input and distributed-parameter-output system

For the CC machine of Železiarne Podbrezová, Inc. dynamic characteristics of the secondary cooling zone as LDS was obtained using a validated numerical model in ProCAST. The cross section of the strand refers to "billet" (square of size 200 x 200 mm).

The control objective is maintaining a prescribed temperature field of the billet within a given tolerance. A steady-state operation regime – setpoint of the casting machine was considered, i.e. steady-state water flow rates $\{U_i(t)\}_{i=1,5}$ maintaining steady-state temperature field (solidification profile) for particular operating conditions (steel grade, casting velocity and superheat). In a linearized region around the setpoint let us consider a step change of water flow rates for individual cooling sections. By this way we obtain a set of distributed transient characteristics (which are denoted in a discrete time as $\{\boldsymbol{\mathcal{H}H}_i(\overline{\boldsymbol{x}},k)\}_{i=1,5}$. Here, $\overline{\boldsymbol{x}}$ denotes a finite set of nodes from definition domain of the investigated system Ω in a numerical computational scheme. By self-subtracting the time-delayed step responses $\{\boldsymbol{\mathcal{H}H}_i(\overline{\boldsymbol{x}},k)\}_{i=1,5}$ we obtain a set of distributed impulse responses

$$\{\boldsymbol{\mathcal{G}H}_i(\overline{\boldsymbol{x}},k) = \boldsymbol{\mathcal{H}H}_i(\overline{\boldsymbol{x}},k) - \boldsymbol{\mathcal{H}H}_i(\overline{\boldsymbol{x}},k-1)\}_{i=1,5}\,. \tag{2}$$

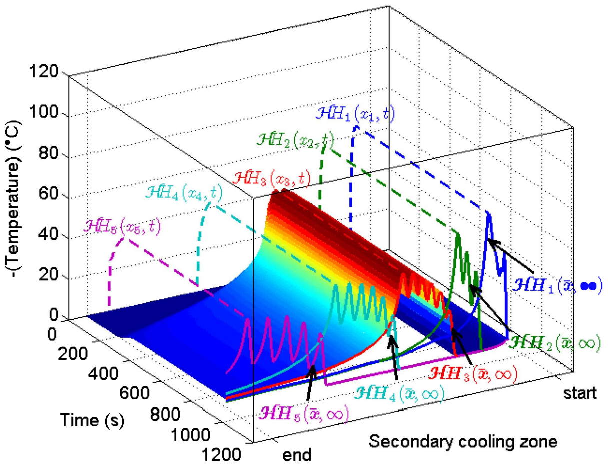

Fig. 6. Distributed transient characteristics for individual flow rate step changes; values of characteristics take negative sign.

Overall discrete-time distributed response of temperature field can be obtained as follows

$$\boldsymbol{Y}(\overline{\boldsymbol{x}},k) = \sum_{i=1}^{5} \boldsymbol{Y}_i(\overline{\boldsymbol{x}},k) = \sum_{i=1}^{5} \boldsymbol{\mathcal{G}H}_i(\overline{\boldsymbol{x}},k) \oplus U_i(k) \tag{3}$$

with $\oplus$ denoting discrete convolution.

For each distributed transient characteristic, a time course with highest gain is selected (dashed line, Fig. 7). For secondary cooling zones in general, highest-gain points are located right below the corresponding cooling section (downstream the casting direction). For five cooling sections, there are five such points $\overline{x} = \{x_i\}_{i=1,5} \subseteq \Omega$. For time courses in those points $\{\mathcal{H}H_i(x_i,k)\}_{i=1,5}$, Fig. 7, let us now assign corresponding transfer functions $\{SH_i(x_i,z)\}_{i=1,5}$. These functions represent the time dynamics of the distributed parameter system. Partial output responses $\{\boldsymbol{Y}_i(\overline{\boldsymbol{x}},k)\}_{i=1,5}$ in points $\overline{x} = \{x_i\}_{i=1,5} \subseteq \Omega$, i.e. $\{Y_i(x_i,k)\}_{i=1,5}$ can then be calculated as follows

$$\{Y_i(x_i,z) = SH_i(x_i,z)U_i(z)\}_{i=1,5}\,. \tag{4}$$

To obtain dynamics components in space, reduced distributed transient characteristics in steady-state $\{\boldsymbol{\mathcal{H}HR}_i(\overline{\boldsymbol{x}},\infty)\}_{i=1,5}$ have been calculated from distributed transient characteristics as follows

$$\{\boldsymbol{\mathcal{H}HR}_i(\overline{\boldsymbol{x}},\infty) = \boldsymbol{\mathcal{H}H}_i(\overline{\boldsymbol{x}},\infty) / \mathcal{H}H_i(x_i,\infty)\}_{i=1,5}\,, \tag{5}$$

where $\{\mathcal{H}H_i(x_i,\infty)\}_{i=1,5} \neq 0$, Fig. 8.

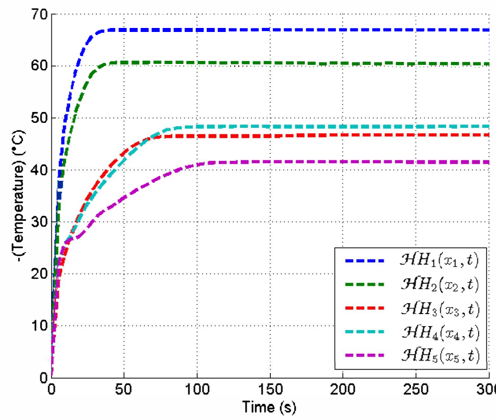

Fig. 7. Selected partial distributed transient characteristics for water flow step changes in all independent cooling sections.

By means of reduced distributed transient characteristics we can calculate steady-state partial responses as follows

$$\{\boldsymbol{Y}_i(\overline{\boldsymbol{x}},\infty) = Y_i(x_i,\infty)\boldsymbol{\mathcal{H}HR}_i(\overline{\boldsymbol{x}},\infty)\}_{i=1,5}\,. \tag{6}$$

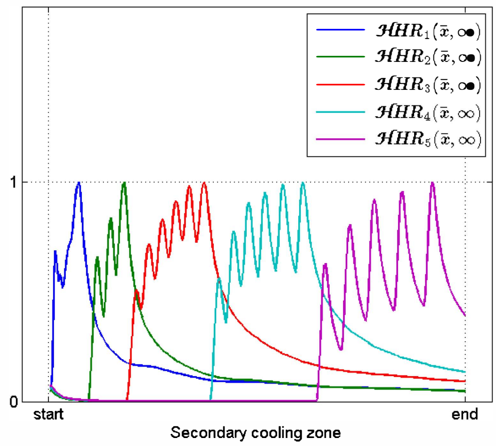

Fig. 8. Reduced distributed transient characteristics in steady-state.

For overall steady-state response it holds

$$\boldsymbol{Y}(\bar{\boldsymbol{x}},\infty)=\sum_{i=1}^{5} Y_i(x_i,\infty)\,\mathcal{H}\boldsymbol{HR}_i(\bar{\boldsymbol{x}},\infty). \tag{7}$$

Similarly, it is possible to introduce reduced distributed output responses using (3) and (4) as follows

$$\{\boldsymbol{YR}_i(\bar{\boldsymbol{x}},k)\}_i=\{\boldsymbol{Y}_i(\bar{\boldsymbol{x}},k)/Y_i(x_i,k)\}_{i=1,5}, \tag{8}$$

$\{Y_i(x_i,k)\neq 0\}_i$. Rewriting (8) for time step k yields

$$\{\boldsymbol{Y}_i(\bar{\boldsymbol{x}},k)=Y_i(x_i,k)\boldsymbol{YR}_i(\bar{\boldsymbol{x}},k)\}_{i=1,5}. \tag{9}$$

III. Control Synthesis

Having both time and space components of the secondary cooling zone dynamics, we design the DPS control loop for control of billet temperature field using water flow rates as control variables, Fig. 9.

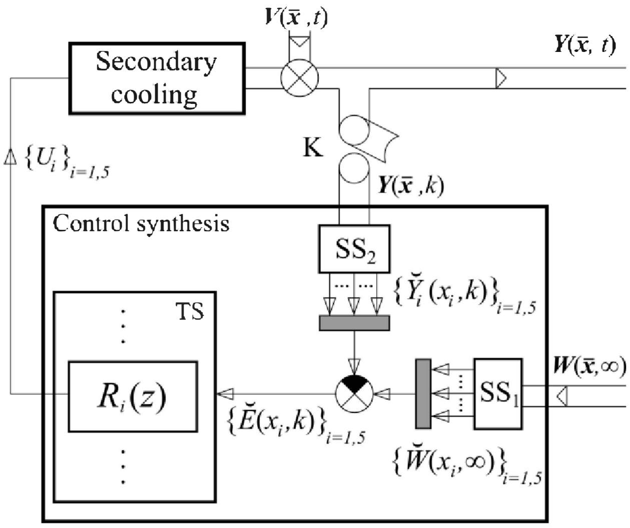

Fig. 9. DPS control loop.

Let us now describe the control process on $\bar{\boldsymbol{x}}\in\Omega$ in detail; we will further consider a linearized region of selected setpoint, being the new zero state. Next, let a step change in reference variable $\boldsymbol{W}(\bar{\boldsymbol{x}},\infty)$ take place in the control system. We assume that the convolution model (3) remains valid and further $\boldsymbol{V}(\bar{\boldsymbol{x}},t)=0$ holds. The control goal in space is to minimize quadratic norm $\|.\|_2$ of distributed steady-state control error $\boldsymbol{E}(\bar{\boldsymbol{x}},\infty)$, the control objective in time domain will be discussed later. In the actual control process, approximation problem is being solved in block SS_1, Fig. 9:

$$\min_{W_i}\left\|\boldsymbol{W}(\bar{\boldsymbol{x}},\infty)-\sum_{i=1}^{5}W_i(x_i,\infty)\,\mathcal{H}\boldsymbol{HR}_i(\bar{\boldsymbol{x}},\infty)\right\|_2. \tag{10}$$

Similarly in block SS_2, approximation problem is being solved, taking form as follows

$$\min_{Y_i}\left\|\boldsymbol{Y}(\bar{\boldsymbol{x}},k)-\sum_{i=1}^{5}Y_i(x_i,k)\boldsymbol{YR}_i(\bar{\boldsymbol{x}},k)\right\|_2. \tag{11}$$

When $k\to\infty$ the problem (11) transforms into the approximation problem on the set $\{\mathcal{H}\boldsymbol{HR}_i(\bar{\boldsymbol{x}},\infty)\}_{i=1,5}$:

$$\min_{Y_i}\left\|\boldsymbol{Y}(\bar{\boldsymbol{x}},k)-\sum_{i=1}^{5}Y_i(x_i,k)\,\mathcal{H}\boldsymbol{HR}_i(\bar{\boldsymbol{x}},\infty)\right\|_2, \tag{12}$$

for in steady-state it holds $\{\boldsymbol{YR}_i(\bar{\boldsymbol{x}},\infty)=\mathcal{H}\boldsymbol{HR}_i(\bar{\boldsymbol{x}},\infty)\}_{i=1,5}$.

From approximation theory it is well known that solving such problems over strictly convex normed linear subspaces of distributed quantities/infinite-dimensional functions we obtain the unique best approximations:

$$\breve{\boldsymbol{W}}(\bar{\boldsymbol{x}},\infty)=\sum_{i=1}^{5}\breve{W}_i(x_i,\infty)\,\mathcal{H}\boldsymbol{HR}_i(\bar{\boldsymbol{x}},\infty) \tag{13}$$

$$\breve{\boldsymbol{Y}}(\bar{\boldsymbol{x}},k)=\sum_{i=1}^{5}\breve{Y}_i(x_i,k)\boldsymbol{YR}_i(\bar{\boldsymbol{x}},k) \tag{14}$$

$$\breve{\boldsymbol{Y}}(\bar{\boldsymbol{x}},\infty)=\sum_{i=1}^{5}\breve{Y}_i(x_i,\infty)\,\mathcal{H}\boldsymbol{HR}_i(\bar{\boldsymbol{x}},\infty) \tag{15}$$

Approximants (13), (14) and (15) represent the best approximation of reference and controlled variables in k-th time step and steady-state, respectively. Coefficients of approximation $\{\breve{W}_i(x_i,\infty)\}_{i=1,5}$, $\{\breve{Y}_i(x_i,k)\}_{i=1,5}$ and $\{\breve{Y}_i(x_i,\infty)\}_{i=1,5}$ are optimal parameters of presented approximation problems with $\{\breve{Y}_i(x_i,k)=Y_i(x_i,k)\}_{i=1,5}$, according to (7) and (8). In block SS_2 we obtain the vector of lumped quantities for time step k: $\{\breve{Y}_i(x_i,k)=Y_i(x_i,k)\}_{i=1,5}$. Relating $\{U_i(k)\}_{i=1,5}$ with $\{Y_i(x_i,k)\}_{i=1,5}$ transfer functions $\{SH_i(x_i,z)\}_{i=1,5}$ were introduced (4). The quantities $\breve{Y}_i(x_i,k)$, $\breve{W}_i(x_i,\infty)$, $\breve{E}(x_i,k)$ and $U_i(k)$ are connected by relations of simple one-parameter time control loops, Fig. 10, where lumped-parameter input quantities are generated by means of $\{R_i(z)\}_{i=1,5}$ controllers.

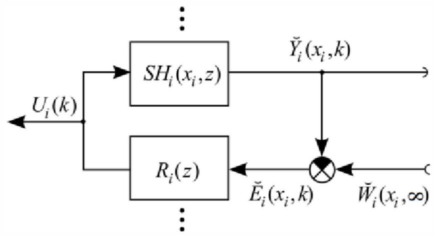

Fig. 10. One-parameter control loops for $\{R_i(z)\}_{i=1,5}$ tuning.

This allows us to utilize all known approaches in lumped-parameter control theory when designing the controllers $\{R_i(z)\}_{i=1,5}$. Our decision on control strategy in one-parameter control loops thus affects the desired transition from initial to steady-state, when $\{\breve{Y}_i(x_i,\infty)=\breve{W}_i(x_i,\infty)\}_{i=1,5}$. If in steady-state the relation $\{\breve{Y}_i(x_i,\infty)=\breve{W}_i(x_i,\infty)\}_{i=1,5}$ holds, then according to (13) and (15) the relation $\breve{\boldsymbol{Y}}(\overline{\boldsymbol{x}},\infty)=\breve{\boldsymbol{W}}(\overline{\boldsymbol{x}},\infty)$ holds, too. This means that the distributed output quantity represents the best approximation of distributed reference quantity. This implies also that the distributed control error $\boldsymbol{E}(\overline{\boldsymbol{x}},\infty)=\boldsymbol{W}(\overline{\boldsymbol{x}},\infty)-\breve{\boldsymbol{Y}}(\overline{\boldsymbol{x}},\infty)=\boldsymbol{W}(\overline{\boldsymbol{x}},\infty)-\breve{\boldsymbol{W}}(\overline{\boldsymbol{x}},\infty)$ in steady-state reaches its minimum. The control goal in space is thus accomplished.

IV. Co-simulation

For benchmark simulation studies of temperature field modeling and control, a co-simulation system consisting of ProCAST and DPS Blockset has been developed at the Slovak University of Technology in Bratislava. ProCAST, a product of the French ESI Group is based on finite element method, serves the engineers as the virtual software environment for both shape and continuous casting technology.

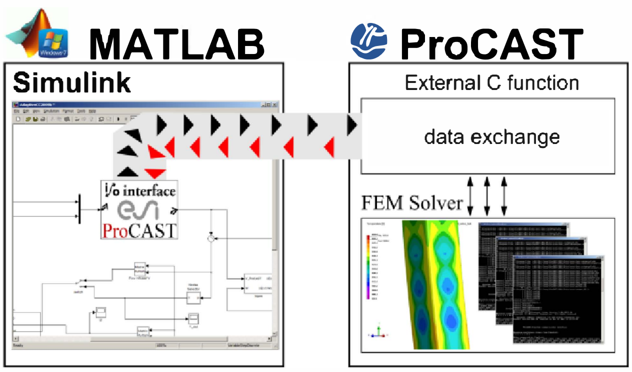

Fig. 11. Data exchange via interface block from DPS Blockset library during Simulink – ProCAST simulation.

ProCAST is the result of more than 20 years of collaboration with major industrial partners and academic institutions all over the world. Distributed Parameter Systems Blockset for MATLAB & Simulink – DPS Blockset has been designed and developed at the Center for Control of DPS, Slovak University of Technology in Bratislava, taking part of The MathWorks' CONNECTIONS program.

V. Controlled Cooling Of Billet Surface In Secondary Cooling Zone

As a simple demonstration of presented approach, let us define the control goal as follows: let the casting machine be in given setpoint with steady-state temperature profile expressed in Fig. 13 by the green curve. In a linearized neighborhood of this state, let the control process take place such as to cool the billet uniformly by 30 °C, represented by reference variable $\boldsymbol{W}(\overline{\boldsymbol{x}},\infty)$ and shown in Fig. 13 and 14 by the red curve. Simulation of the control process was performed in a co-simulation regime as in Fig. 12, with simulation results depicted in Fig. 13 and Fig. 14.

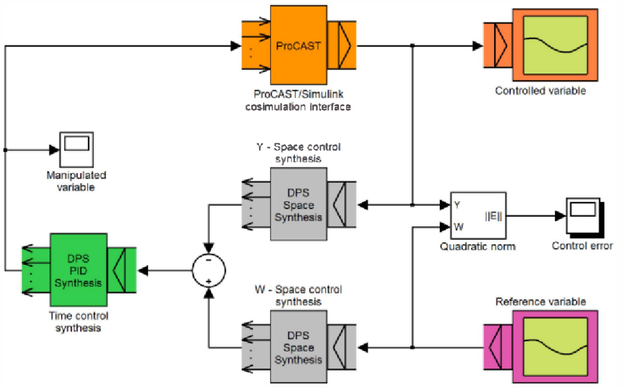

Fig. 12. Co-simulation scheme – parallel cooperation of ProCAST and DPS Blockset.

Physical constraints of spray control valves (fully open/closed) were considered in the SISO controller design. PI1 controllers were used according to [12]. The rate of change of the setpoint is limited in order to avoid reaching the actuator saturation. If this would not be the case, one should impose the constraints to the approximation problem (12). This option is available in the DPS Space Synthesis Block, however it was not included in this case study, since the studied setpoint changes and the controller settings do not require the actuators to saturate.

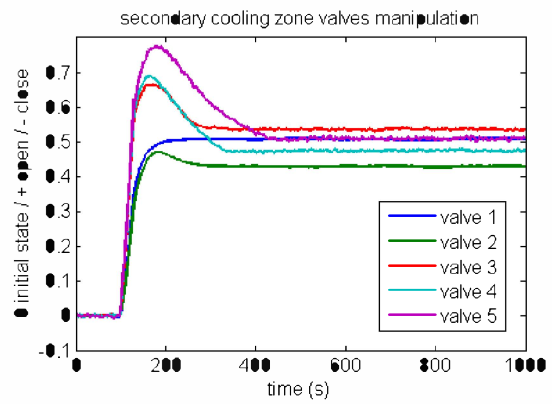

Fig. 13. Manipulation of the valves during setpoint change. (upper bound = 1 / lower bound = -1. 1 stays for fully open valve, -1 for fully closed.)

From technological point of view, using ProCAST gives us a better insight into the control process; after the temperature field of the billet surface reached steady-state, liquid pool length shrank by 0.5 m approximately. This shrinkage can be compensated by increasing the casting velocity, thus boosting the caster productivity if possible; (possibility being limited by furnace productivity), Fig. 15.

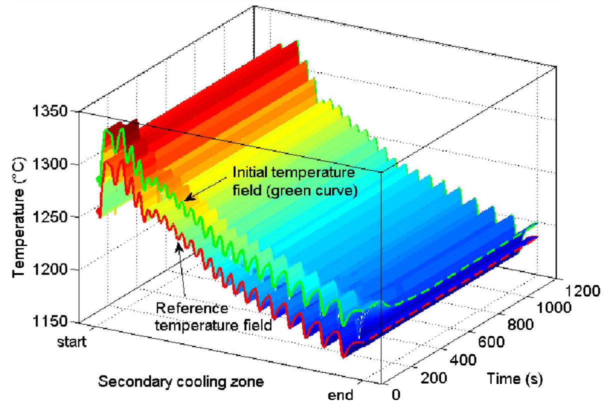

Fig. 14. Start of the co-simulation control process in secondary cooling zone.

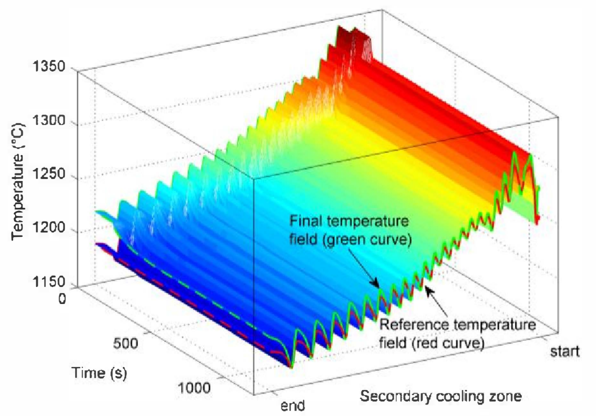

Fig. 15. End of the co-simulation control process in secondary cooling zone.

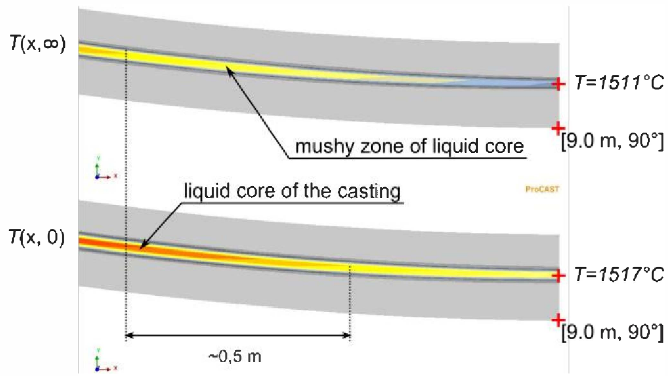

Fig. 16. Liquid core shrinkage of the billet (section prior to unbending zone). Comparison of steady-state temperature field before (below) and after the control process.

VI. Conclusions

Today's advancement in computer and information technology causes new as well as revamped casting plants to be equipped with numerical on-line thermal models of the continuous casting processes. These models help plant managers and technologists to get better insight into the process, so to manage plant production closer to an optimal manner [13], [14]. By connecting these on-line thermal models with suitable control software environment as was presented in this paper via ProCAST-DPS Blockset co-simulation scheme Fig. 12, a new level of control possibilities emerges for control of secondary cooling zone in continuous casting processes.

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