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USE OF COSIMULATION ON CONTROL OF CASTING MOLD PREHEATING PROCESS AS DISTRIBUTED PARAMETERS SYSTEM

VYUŽITIE KOSIMULÁCIE PRI RIADENÍ PREDOHREVU ZLIEVARENSKEJ FORMY AKO SYSTÉMU S ROZLOŽENÝMI PARAMETRAMI

Abstract

The paper deals with problematics of the control of the casting mold preheating process as a distributed parameters system. At the beginning the casting mold and the concept of the distributed parameters systems are introduced. Then there are descriptions of a model designed in COMSOL Multiphysics, system identification and a prepared scheme model for controllers parameters settings in the MATLAB & Simulink environment with advanced product DPS Blockset for MATLAB & Simulink. In the end cosimulation of the software tools COMSOL Multiphysics and MATLAB & Simulink is described and achieved results are analyzed.

Abstrakt

Predkladaný článok rieši problematiku riadenia predohrevu zlievarenskej formy ako systému s rozloženými parametrami. Úvodom je predstavená zlievarenská forma a následne je uvádzaný koncept systémov s rozloženými parametrami. Následne je opísaný model vytvorený v COMSOL Multiphysics. Po vykonanej identifikácií je opísaný prípravný obvod na nastavenie parametrov regulátorov v prostredí MATLAB & Simulink s nadstavbovým produktom DPS Blockset pre MATLAB & Simulink. Na záver článku je opísaná kosimulácia programov COMSOL Multiphysics a MATLAB & Simulink a zhodnotenie dosiahnutých výsledkov.

Keywords

preheating foundry molds, system with distributed parameters, simulation, cosimulation, identification, control synthesis, DPS Blockset.

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1 SYSTEMS WITH DISTRIBUTED PARAMETERS, DYNAMIC OF CONTROL SYSTEM

Technological processes having a continuum-based nature, are generally described by Partial Differential Equations (PDE) and in the sense of systems and control theory are understood as Distributed Parameter Systems (DPS). In most practical cases we introduce this description in a linearized neighborhood of the controlled system‘s steady state operating points thus obtaining a linear PDE. Distributed quantities from the right and left sides of PDE in input/output relation give Distributed input and Distributed parameter output Systems or simply Distributed input and Distributed output Systems (DDS), Fig. 1.

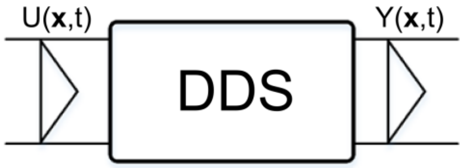


Fig. 1. Systém s rozloženým vstupom a rozloženým výstupom.

In the case of preheating the mold actuating variables are given as currents of each heating zone and controlled variable is the temperature field. It is generally a lumped input and distributed parameter output system, which as a controlled system of a discrete control loop is discrete lumped input and distributed parameter output systems with zero order hold units - HLDS, with lumped input quantities $\{U_i(k)\}_{i=1,5}$ and distributed parameter output quantity $Y(\boldsymbol{x},t)=Y(x,y,z,t)$, Fig. 2.

Fig. 2. Discrete lumped input and distributed parameter output system with zero order hold units.

During the application of discrete unit step changes $\{U_i(k)=1(k)\}_{i=1,5}$ we receive discrete distributed parameter transient characteristics $\{\mathcal{H}H_i(\boldsymbol{x},k)\}_{i=1,5}$. Subtracting the shifted distributed transient characteristics we get distributed impulse characteristics $\{\mathcal{G}H_i(\boldsymbol{x},k)=\mathcal{H}H_i(\boldsymbol{x},k)-\mathcal{H}H_i(\boldsymbol{x},k-1)\}_{i=1,5}$. Then

$$Y(\boldsymbol{x},k)=\sum_{1}^{5}Y_i(\boldsymbol{x},k)=\sum_{1}^{5}\mathcal{G}H_i(\boldsymbol{x},k)\oplus U_i(k) \tag{1}$$

where $\{Y_i(\boldsymbol{x},k)\}_{i=1,5}$ are partial distributed output quantities of HLDS and $\oplus$ is the symbol of discrete convolution

In steady state

$$Y(\boldsymbol{x},\infty)=\sum_{1}^{5}Y_i(\boldsymbol{x},\infty)=\sum_{1}^{5}\mathcal{H}H_i(\boldsymbol{x},\infty)U_i(\infty) \tag{2}$$

In the definition domain of controlled system we choose points where each distributed transient characteristics in steady state reached its maximum values $\{\mathcal{H}H_i(\boldsymbol{x}_i,\infty)\}_{i=1,5}$. Then

$$\left\{ Y(\boldsymbol{x}_i,k) = \sum_1^5 Y_i(\boldsymbol{x}_i,k) = \sum_1^5 \mathcal{G}H_i(\boldsymbol{x}_i,k) \oplus U_i(k) \right\}_i \tag{3}$$

For control purposes, let us introduce the following temporal and spatial characteristics of the controlled system:

Time characteristic:

$\left\{\mathcal{H}H_i\left(\boldsymbol{x}_i,k\right)\right\}_{i=1,5}, \left\{\mathcal{H}H_i\left(\boldsymbol{x}_i,\infty\right)\right\}_{i=1,5}, \left\{\mathcal{G}H_i\left(\boldsymbol{x}_i,k\right)\right\}_{i=1,5}$

Space characteristic:

$\left\{\mathcal{H}H_i\left(\boldsymbol{x},k\right)\right\}_{i=1,5}, \left\{\mathcal{H}H_i\left(\boldsymbol{x},\infty\right)\right\}_{i=1,5}, \left\{\mathcal{G}H_i\left(\boldsymbol{x},k\right)\right\}_{i=1,5}$

It is often advantageous for characteristics of the dynamics of controlled system to partial course of $\left\{\mathcal{H}H_i\left(\boldsymbol{x}_i,k\right)\right\}_{i=1,5}$ to assign transfer functions $\left\{SH_i\left(\boldsymbol{x}_i,\mathrm{z}\right)\right\}_{i=1,5}$. In the spatial relation for characteristics of dynamics let us introduce further reduced dynamic characteristics $\left\{\mathcal{G}HR_i(\boldsymbol{x},k) = \mathcal{G}H_i(\boldsymbol{x},k) / \mathcal{G}H_i(\boldsymbol{x}_i,k)\right\}_{i=1,5}$ for $\left\{\mathcal{G}H_i\left(\boldsymbol{x}_i,k\right) \neq 0\right\}_{i=1,5}$.

Similarly we will introduce further reduced waveforms of partial output variables $\left\{YR_i\left(\boldsymbol{x},k\right) = Y_i\left(\boldsymbol{x},k\right) / Y_i\left(\boldsymbol{x}_i,k\right)\right\}_{i=1,5}$ pre $\left\{Y_i\left(\boldsymbol{x}_i,k\right) \neq 0\right\}_{i=1,5}$ then

$$Y(\boldsymbol{x},k) = \sum_1^5 Y_i(\boldsymbol{x},k) = \sum_i \mathcal{G}H_i(\boldsymbol{x},k) \oplus U_i(k) = \sum_1^5 Y_i(\boldsymbol{x}_i,k) YR_i(\boldsymbol{x},k) \tag{4}$$

In doing so in the steady state $Y(\boldsymbol{x},\infty) = \sum_1^5 Y_i(\boldsymbol{x},\infty) = \sum_1^5 Y_i(\boldsymbol{x}_i,\infty) YR_i(\boldsymbol{x},\infty) = \sum_1^5 Y_i(\boldsymbol{x}_i,\infty) \mathcal{H}H_i\left(\boldsymbol{x},\infty\right)$

because

$$\left\{YR_i\left(\boldsymbol{x},\infty\right) = Y_i\left(\boldsymbol{x},\infty\right) / Y_i\left(\boldsymbol{x}_i,\infty\right) = U_i\left(\infty\right) \mathcal{H}H_i\left(\boldsymbol{x},\infty\right) / U_i\left(\infty\right) \mathcal{H}H_i\left(\boldsymbol{x}_i,\infty\right) = \mathcal{H}HR_i\left(\boldsymbol{x},\infty\right)\right\}_i \tag{5}$$

Pursuant equation (4) also pays

$$\begin{bmatrix} Y\left(\boldsymbol{x}_1,k\right) \\ \vdots \\ Y\left(\boldsymbol{x}_i,k\right) \\ \vdots \\ Y\left(\boldsymbol{x}_5,k\right) \end{bmatrix} = \begin{bmatrix} YR_1\left(\boldsymbol{x}_1,k\right) & ,..., & YR_i\left(\boldsymbol{x}_1,k\right) & ,..., & YR_5\left(\boldsymbol{x}_1,k\right) \\ & & & & \\ YR_1\left(\boldsymbol{x}_i,k\right) & ,..., & YR_i\left(\boldsymbol{x}_i,k\right) & ,..., & YR_5\left(\boldsymbol{x}_i,k\right) \\ & & & & \\ YR_1\left(\boldsymbol{x}_5,k\right) & ,..., & YR_i\left(\boldsymbol{x}_5,k\right) & ,..., & YR_5\left(\boldsymbol{x}_5,k\right) \end{bmatrix} \begin{bmatrix} Y_1\left(\boldsymbol{x}_1,k\right) \\ \vdots \\ Y_i\left(\boldsymbol{x}_i,k\right) \\ \vdots \\ Y_5\left(\boldsymbol{x}_5,k\right) \end{bmatrix} \tag{6}$$

Near steady-state for $k \to \infty$ waveforms $\left\{YR_i\left(\boldsymbol{x},k\right)\right\}_{i=1,5}$ converge to the courses of $\left\{\mathcal{H}HR_i\left(\boldsymbol{x},\infty\right)\right\}_{i=1,5}$, the relation (6), therefore for calculation of values $\left\{Y_i\left(\boldsymbol{x}_i,k\right)\right\}_{i=1,5}$ based on the $\left\{Y\left(\boldsymbol{x}_i,k\right)\right\}_{i=1,5}$ for $k \to \infty$ we can consider with an approximate relation

$$\begin{bmatrix} Y(\boldsymbol{x}_1,k) \\ \vdots \\ Y(\boldsymbol{x}_i,k) \\ \vdots \\ Y(\boldsymbol{x}_5,k) \end{bmatrix} \mathrm{B} \begin{bmatrix} \mathcal{H}HR_1(\boldsymbol{x}_1,\infty),...,\mathcal{H}HR_i(\boldsymbol{x}_1,\infty),...,\mathcal{H}HR_5(\boldsymbol{x}_1,\infty) \\ \\ \mathcal{H}HR_1(\boldsymbol{x}_i,\infty),...,\mathcal{H}HR_i(\boldsymbol{x}_i,\infty),...,\mathcal{H}HR_5(\boldsymbol{x}_i,\infty) \\ \\ \mathcal{H}HR_1(\boldsymbol{x}_5,\infty),...,\mathcal{H}HR_i(\boldsymbol{x}_5,\infty),...,\mathcal{H}HR_5(\boldsymbol{x}_n,\infty) \end{bmatrix} \begin{bmatrix} Y_1(\boldsymbol{x}_1,k) \\ \vdots \\ Y_i(\boldsymbol{x}_i,k) \\ \vdots \\ Y_5(\boldsymbol{x}_5,k) \end{bmatrix} \tag{7}$$

and an abridged form of

$$\bar{Y}(\boldsymbol{x}_i,k)\,\mathrm{B}\,\bar{\mathcal{H}}HR_i(\boldsymbol{x}_j,\infty)\bar{Y}_i(\boldsymbol{x}_i,k) \tag{8}$$

where $\bar{Y}(\boldsymbol{x}_i,k)=\{Y(\boldsymbol{x}_1,k),...,Y(\boldsymbol{x}_5,k)\}^T$ a $\bar{Y}_i(\boldsymbol{x}_i,k)=\{Y_1(\boldsymbol{x}_1,k),...,Y_5(\boldsymbol{x}_5,k)\}^T$.

Then, after the inversion of matrix $\bar{\mathcal{H}}HR_i(\boldsymbol{x}_j,\infty)$

$$\bar{Y}_i(\boldsymbol{x}_i,k)\,\mathrm{B}\,\bar{\mathcal{H}}HR_i(\boldsymbol{x}_j,\infty)^{-1}\bar{Y}(\boldsymbol{x}_i,k) \tag{9}$$

2 EXPERIMENTAL DEVICE OF CONTROLLED CASTING

Experimental device for analyzing the possibilities of controlled preheating of the casting mold and active cooling of casting material is located in Laboratory of modeling and control of technological and production processes in Institute of Automation, Measurement and Applied Informatics SjF STU. The device is equipped by sensors for monitoring of temperature fields and actuators to generate heat and cooling in the body of the mold. All is managed in the environment MATLAB & Simulink, where system for measurement and control in real-time is available.

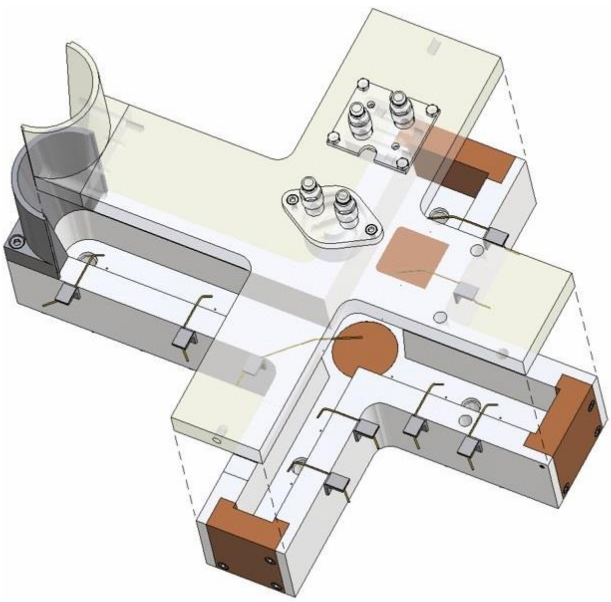


Fig. 3. Model of the casting mold

Design of dealt problem come from casting technology needs, where common construction element – crossed joint – is classic problem from the view of draws occurance causing by thermal knot that rise in this place. In this construction order the frames of the cast have different profile by which is designing and synchronization of solidification of the frames influenced.

Another problem of greater distance thermal knot and feeder is included and this creates harder abutting of liquid metal into solid cast.

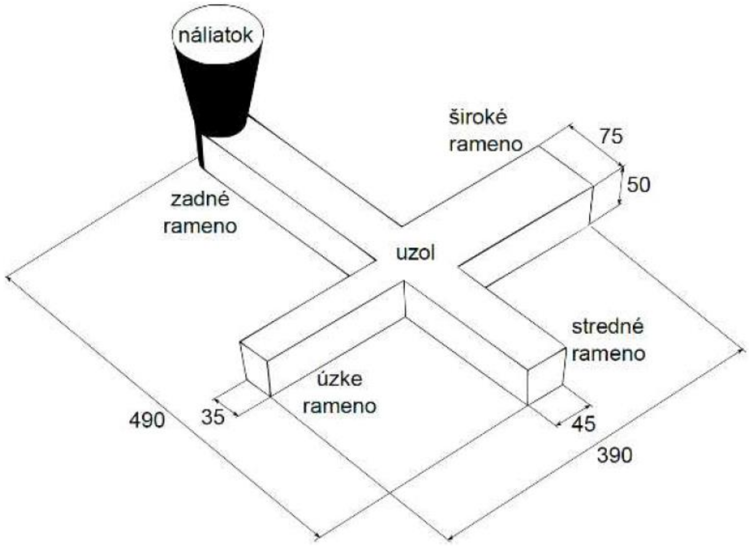


Fig. 4. Shape and dimensions of designed cast

Mold preheating technology

Heating circle

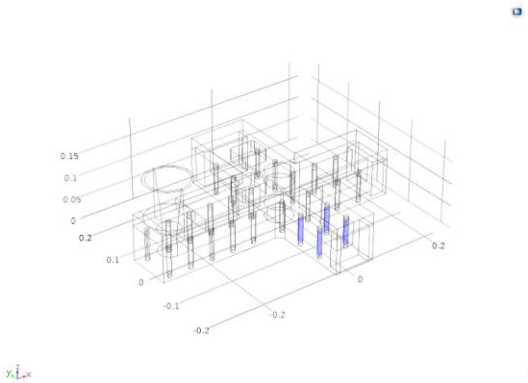
Heat output needed provide 26 embedded electric resistance members, each with nominal power 400W divided into five zones, Tab. 1, Fig. 3.

Tab. 1. COUNT OF HEATING ELEMENTS IN GIVEN ZONE AND NOMINAL PWOER.

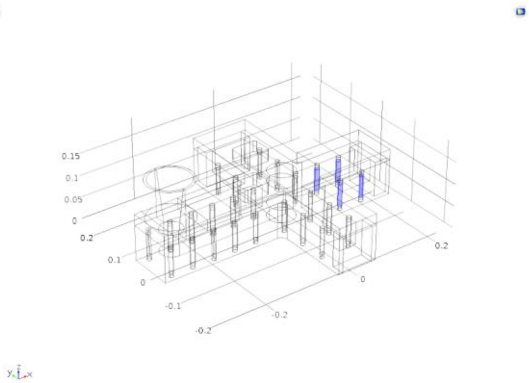
Zone	*Count of heating elements*	*Nominal power (W)*	*Power during simulation (W)*
1	4	1600	320
2	4	1600	320
3	4	1600	320
4	6	2400	480
5	8	3200	640

Overall installed power is 10.4kW. The mold temperature is measured by thermocouples. Number and power of elements is designed with sense of needs to reach required temperature fast while having in mind it is system with considerable capacitive delay.

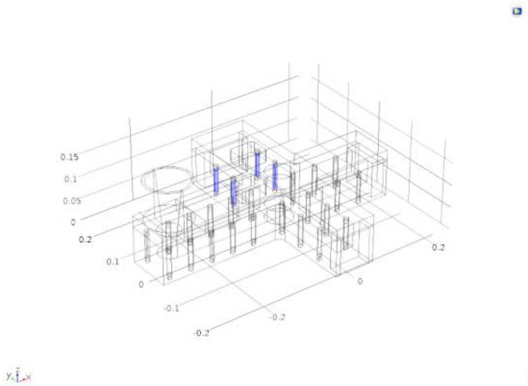
Used heating elements are BACKER ELEKTRO 2303/360, connected by thyristor switching units Honeywell CD-3000S with single-phase voltage 230V, which are controlled through voltage signal 0 – 10V from measuring card HUMUSOFT AD622 over distribution HUMUSOFT TB620.



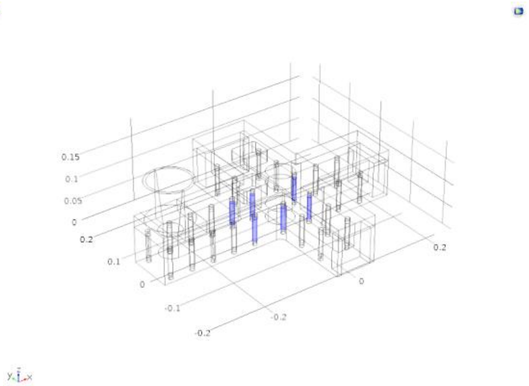
First zone



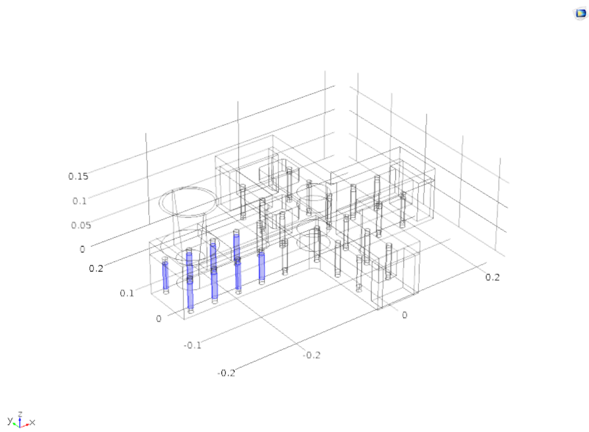
Second zone



Third zone



Fourth zone



Fifth zone

Fig. 5. Heating zones localization on the casting mold

Measurement circle

Thermoelectric sensor probes are OMEGA TJ36 with cell type K (NiCr-NiAl), connected via compesating cable plugged to the transmitters AUDON TCK-4, which in turn send a voltage signal 0 – 10V to swithboard measuring card ADVANTECH PCLD-8710.

Tab. 2. NUMBERING AND POSITION OF THERMOCOUPLES

Axis/thermoc.	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*
x (m)	0	0	0	0,145	0,09	0,035	0	0	-0,035	-0,145	-0,255
y (m)	0,1585	0,0985	0,05	0	0	0	-0,135	-0,075	0	0	0
z (m)	0,03	0,03	0,03	0,03	0,03	0,03	0,03	0,03	0,03	0,03	0,03

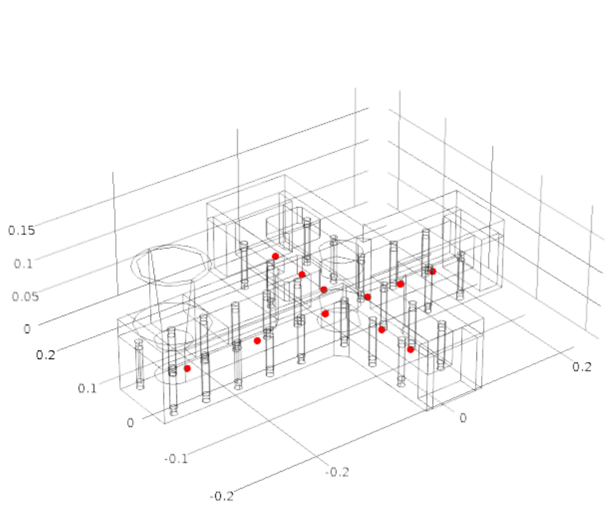


Fig. 6. Position of thermocouples on the casting mold

Software interface

Device communication with the user is ensured in environment MATLAB & Simulink by utility scheme. Communication with particular hardware secure drivers ADVANTECH a HUMUSOFT, with use of Real-Time Window Target that insure system functions in real-time

3 DESIGN OF CONTROL SYSTEM

Let us consider control loop with distributed parameters in the following configuration, Fig. 7.

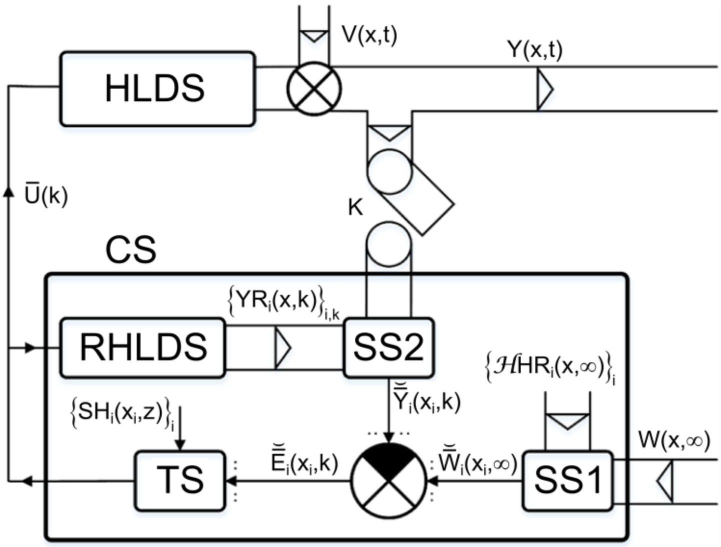


Fig. 7. Closed-loop control with RHLDS block.

RHLDS	- model of the controlled system (HLDS) which computes reduced partial responses at the sampling times.
TS	- time synthesis.
PS1,PS2	- space synthesis blocks.
K	- sampling.
$Y(\boldsymbol{x},t)$	- overall continuous distributed output quantity.
$\{YR_i(\boldsymbol{x},k)\}_{i,k}$	- reduced discrete partial distributed output quantities.
$W(\boldsymbol{x},\infty)$	- overall distributed reference/desired quantity in steady state.
$V(\boldsymbol{x},t)$	- distributed disturbance quantity.
$\breve{Y}_i(\boldsymbol{x}_i,k)=\{\breve{Y}_i(\boldsymbol{x}_i,k)\}_{i=1,5}$	- components of the partial output quantity vector.
$\{\breve{W}_i(\boldsymbol{x}_i,\infty)\}_i$	- vector of discrete lumped reference/desired quantities in steady state.
$\breve{E}_i(\boldsymbol{x}_i,k)=\{\breve{E}_i(\boldsymbol{x}_i,k)\}_{i=1,5}$	- components of the partial control error.
$\bar{U}(k)=\{U_i(k)\}_{i=1,5}$	- vector of lumped actuating quantities.
$\{SH_i(\boldsymbol{x}_i,z)\}_{i=1,5}$	- temporal components of the controlled system dynamics.

$\left\{\mathcal{H}HR_i\left(\boldsymbol{x},\infty\right)\right\}_{i=1,5}$ - space components of the controlled system dynamics.

where controlled, reduced controlled, disturbances and dynamical characteristics of HLDS in space direction in individual discrete time steps, resp. in steady state are elements of linear strictly convex normed space of functions $\boldsymbol{X}$.

The aim of control is to minimize the steady-state control deviation $E\left(\boldsymbol{x},\infty\right)=W\left(\boldsymbol{x},\infty\right)-Y\left(\boldsymbol{x},\infty\right)$ in quadratic norm. In block PS1 an approximation task is solved on the finite set of approximation functions $\left\{\mathcal{H}HR_i\left(\boldsymbol{x},\infty\right)\right\}_{i=1,5}$, that form the basis of a linear subspace of functions Fn on $\boldsymbol{X}$.

$$\min\left\|W\left(\boldsymbol{x},\infty\right)-\sum_{i=1}^{n}W_i\left(\boldsymbol{x}_i,\infty\right)\mathcal{H}HR_i\left(\boldsymbol{x},\infty\right)\right\|=\left\|W\left(\boldsymbol{x},\infty\right)-\sum_{i=1}^{n}\breve{W}_i\left(\boldsymbol{x}_i,\infty\right)\mathcal{H}HR_i\left(\boldsymbol{x},\infty\right)\right\| \tag{10}$$

The presented formulation guarantees the existence and uniqueness of solutions of approximation task with the vector of optimal values of approximating parameter $\left\{\breve{W}_i\left(\boldsymbol{x}_i,\infty\right)\right\}_{i=1,5}$ with the minimum value of the quadratic norm between $W\left(\boldsymbol{x},\infty\right)$ and its best approximation

$$\breve{W}O\left(\boldsymbol{x},\infty\right)=\sum_{i=1}^{n}\breve{W}_i\left(\boldsymbol{x}_i,\infty\right)\mathcal{H}HR_i\left(\boldsymbol{x},\infty\right) \tag{11}$$

In the block PS2 similarly the approximation problem is solved, where reduced output waveforms $\left\{YR_i\left(\boldsymbol{x},k\right)\right\}_{i,k}$, generated in block RHSSR, now are considered as basis functions of finite linear subspace of functions Yn on $\boldsymbol{X}$. In terms of equation (4) under the action of the same sequence actuating quantities $\bar{U}\left(k\right)$ to block HLDS as well as block RHLDS $Y\left(x,k\right)\in Yn$. Then

$$\min\left\|Y\left(\boldsymbol{x},k\right)-\sum_{i=1}^{n}Y_i\left(\boldsymbol{x}_i,k\right)YR_i\left(\boldsymbol{x},k\right)\right\|=\left\|Y\left(\boldsymbol{x},k\right)-\sum_{i=1}^{n}\breve{Y}_i\left(\boldsymbol{x}_i,k\right)YR_i\left(\boldsymbol{x},k\right)\right\|=0 \tag{12}$$

which gives the vector $\left\{\breve{Y}_i\left(\boldsymbol{x}_i,k\right)\right\}_{i=1,5}$.

Finally in algebraic block control deviation is equal to

$$\left\{\breve{E}_i\left(\boldsymbol{x}_i,k\right)=\breve{W}_i\left(\boldsymbol{x}_i,k\right)-\breve{Y}_i\left(\boldsymbol{x}_i,k\right)\right\}_{i=1,5} \tag{13}$$

In block TS there are regulators $\left\{R_i\left(z\right)\right\}_{i=1,5}$, which are tunned by control loops $\left\{SH_i\left(\boldsymbol{x}_i,z\right),R_i\left(z\right)\right\}_{i=1,5}$, Fig. 8 so that in the steady state for $k\to\infty$ the relation $\left\{\breve{W}_i\left(\boldsymbol{x}_i,\infty\right)-\breve{Y}_i\left(\boldsymbol{x}_i,\infty\right)=\breve{E}\left(\boldsymbol{x}_i,\infty\right)=0\right\}_{i=1,5}$.

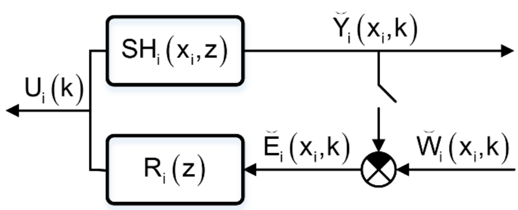


Fig. 8. i-th control loop for tuning rugulator $R_i\left(z\right)$.

So in steday state of control process $\left\{\breve{W}_i\left(\boldsymbol{x}_i,\infty\right)=\breve{Y}_i\left(\boldsymbol{x}_i,\infty\right)\right\}_{i=1,5}$ holds and within the meaning of relations (5) and (11) the distributed control quantity $\breve{Y}\left(x,\infty\right)$ gives the best approximation of the control quantity $W\left(\boldsymbol{x},\infty\right)$

$$\begin{aligned}\breve{Y}(\boldsymbol{x},\infty)&=\sum_{1}^{5}\breve{Y}_i(\boldsymbol{x}_i,\infty)YR_i(\boldsymbol{x},\infty)=\sum_{1}^{5}\breve{Y}_i(\boldsymbol{x}_i,\infty)\mathcal{H}H_i\left(\boldsymbol{x},\infty\right)=\\&=\sum_{1}^{5}\breve{W}_i(\boldsymbol{x}_i,\infty)\mathcal{H}H_i\left(\boldsymbol{x},\infty\right)=\breve{W}O\left(\boldsymbol{x},\infty\right)\end{aligned}\tag{14}$$

4 DYNAMICS IDENTIFICATION OF THE CASTING MOLD

For identification of the preheating dynamics of the casting mold needs firstly CAD model of the casting mold had to be imported into software tool COMSOL Multiphysic. Then the boundary and initial conditions, heat transfers between individual parts of the mold had to be defined. Heating elements were defined into five heating zones according to real wiring on casting mold. Precise placement of heating and sensor components in the casting mold can be seen in Fig. 3 and Fig. 4. The software COMSOL Multiphysic is a program working with finite element method, therefore on the imported model a mesh was created for computational needs, Fig. 9.

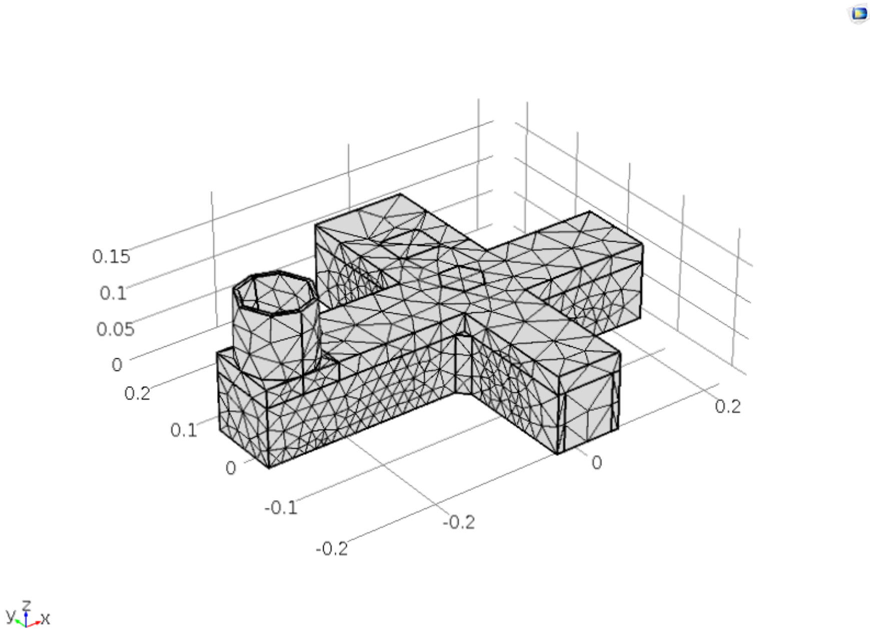


Fig. 9. Mesh created on the model of the casting mold in software COMSOL Multiphysics.

After the mesh was created the simulation of the preheating was executed. In the casting mold are embedded heating elements with nominal power 400 W each and are connected into individual heating zones as was mentioned before. During simulations of preheating of the casting mold a step changes of overall powers at specific zones were done by 20 % from total power of the zone.

In Tab. 1 are listed count of the heating elements in given zone, nominal power of the zone and velocity of power step change in simulation of preheating for necessity of identification of casting mold dynamics.

Step response characteristics acquired after step change of power in fourth zone can be seen in Fig. 10. Step response characteristics for the rest zones were done similarly. These characteristics underwent identification process in order to obtain model of the casting mold.

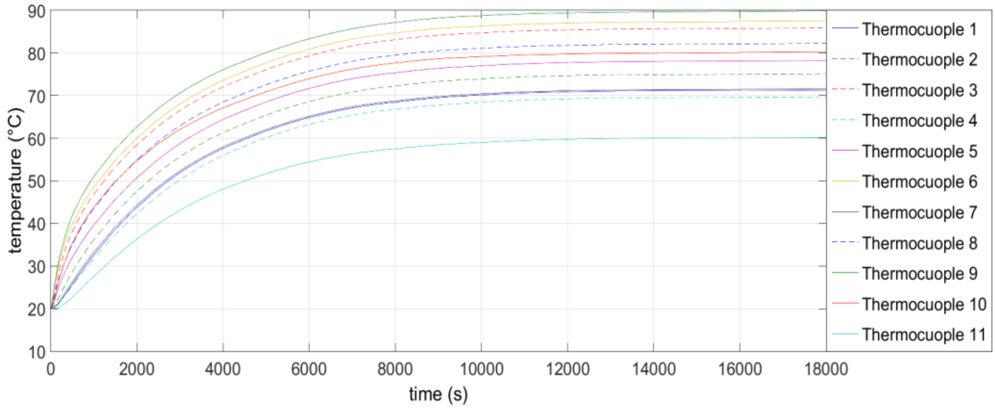


Fig. 10. Step response characteristics after step change of power in fourth zone.

In Fig. 11 is temperature field in steady-state of the casting mold in the software COMSOL Multiphysics.

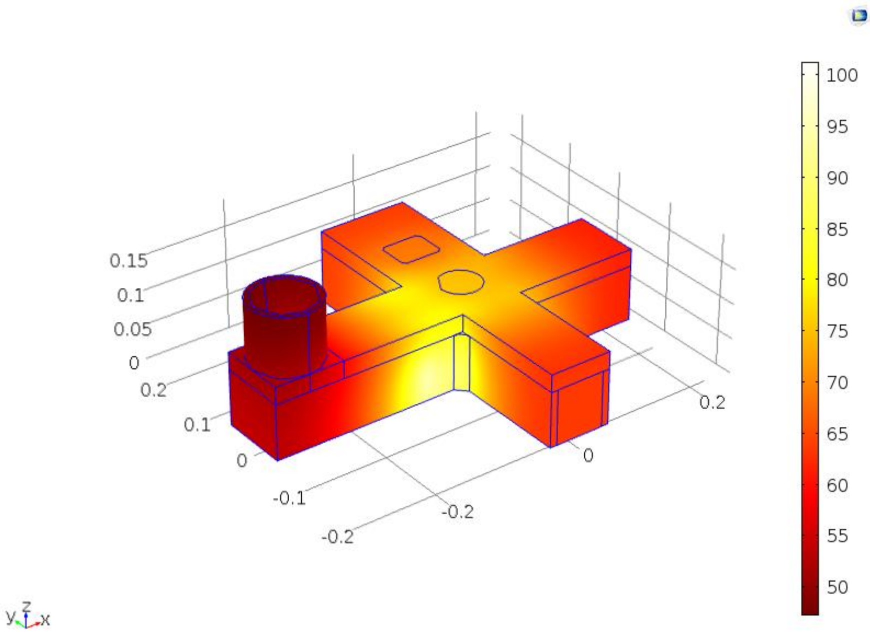


Fig. 11. Steady-state of temperature field of the casting mold in COMSOL Multiphysics.

Step response with the fastest dynamics was selected from the other ones for the identification needs. The fastest dynamics is selected therefore it is the best representation of heating dynamics of the zone. For that the identification Toolbox was used in MATLAB software environment. Unit step change was considered as the input lasting at all time of simulation, sampling time was set the same as in simulation and even in cosimulation that is 30 s. Searched transfer function is in the form (15). In Tab. 3 are identified transfer functions in continuous and discrete domain.

$$\left\{ S_i(s) = \frac{K_i}{T_{pi}s+1} \right\}_{i=1,5} \tag{15}$$

Tab. 3. IDENTIFIED TRANSFER FUNCTIONS AND POSITION OF THERMOCOUPLES WITH THE FASTEST DYNAMICS

Zone	*Position*	$\{S_i(s)\}_{i=1,5}$	$\{S_i(z)\}_{i=1,5}$, *T=30 s*
1	7	$\frac{104,8}{1717s+1}$	$\frac{0,3047}{z-0,9971}$
2	4	$\frac{104,64}{1763,1s+1}$	$\frac{0,2963}{z-0,9972}$
3	1	$\frac{86,12}{2119,6s+1}$	$\frac{0,2029}{z-0,9976}$
4	9	$\frac{89,854}{2606,9s+1}$	$\frac{0,1722}{z-0,9981}$
5	11	$\frac{173,74}{1585,2s+1}$	$\frac{0,5471}{z-0,9969}$

Transfer functions obtained from identification were verified in scheme designed in MATLAB & Simulink with advanced library DPS Blockset, where step changes were made on the input of identified system and the output was monitored if it is identical with data from simulation in COMSOL Multiphysic software tool. Fig. 12 shows steady-state of temperature field after step change of power in fourth zone displayed by DPS Scope that is part of DPS Blockset package. After comparison with Fig. 11 the temperature field of the identified system is coincident with the field in steady-state from COMSOL Multiphysic.

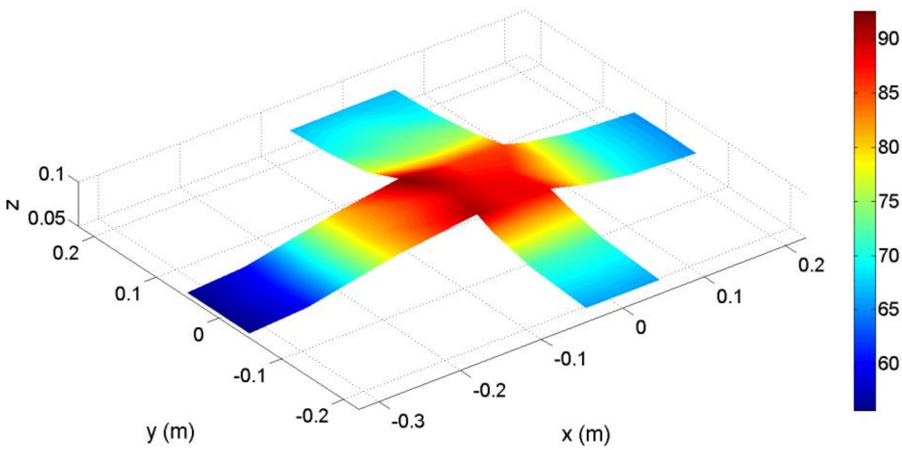


Fig. 12. Temperature field in steady-state of the casting mold displayed from DPS Scope.

5 CONTROL SYSTEM DESIGN IN MATLAB & SIMULINK USING DPS BLOCKSET

Control synthesis was performed in MATLAB & Simulink software environment with use of advanced software library product DPS Blockset. DPS Blockes is specially developed in Institute of Automation, Measurement and Applied Informatics and is a third party product for The Mathworks company. It is the base of distributed parameters system control synthesis. The main part is HLDS block, inside is a field of step response characteristics from individual zones acquired in COMSOL Multiphysics. Another used block is DPS Space Synthesis, where the approximation task is held, which aim is to find fractions of distributed output values in points with the fastest dynamics. With the reference value of the temperature field the output from space synthesis is a vector of partial distributed reference values for each related points. Lastly, the DPS Scope block is used to display, for the needs of thermoset it is displaying the temperature field of the casting mold. To display this output temperature field correctly, DPS Scope requires besides input signal in the vector form also two matrixes. The first has information about co-ordinations, in which are the points, and second has information about relative connection adjacent points. These point is possible pairing by two, three and four points every time in the clockwise direction from initial point.

Input vector has to have length equal to number of points inside the first matrix for correct functionality of DPS Scope. The preheating simulations were performed not only in points where the thermocouples are physically placed inside the casting mold but also for the points that were situated to create a mesh on the bottom part of the mold as the mesh of the points requires for DPS Scope. Thereafter the output quantity is taken as temperature field made from 45 points. And even the reference quantity is entered as temperature field defined in 45 points.

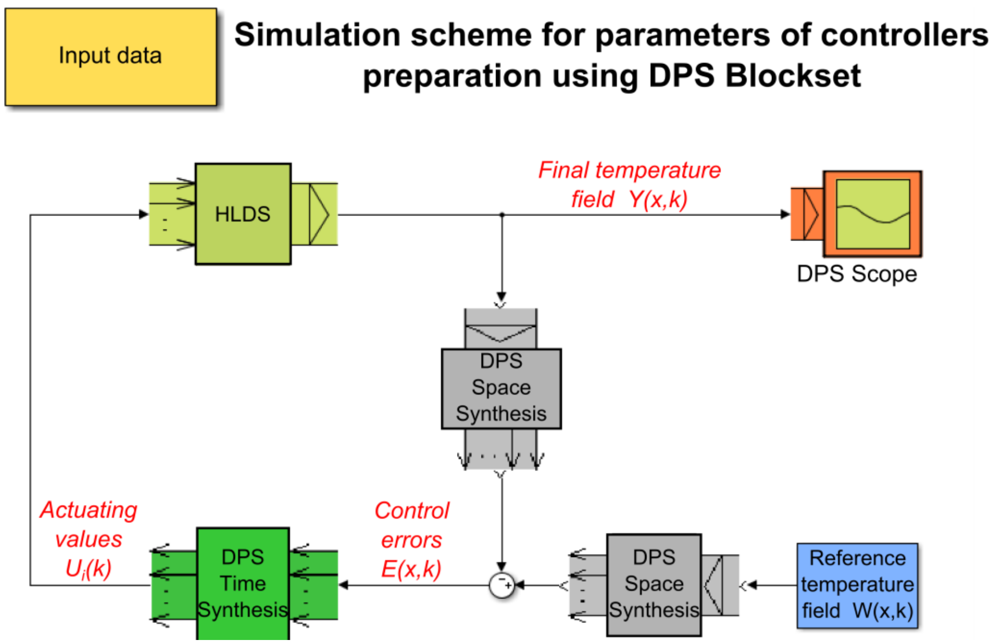


Fig. 13. Simulation scheme for parameters of controllers preparation using DPS Blockset.

Control structure, Fig. 13, was assembled to set and verify the controllers function in control scheme from theoretical experiences introduced above. The control scheme is put together according to Fig. 7.

Fig. 14 illustrates reference temperature field for simulation and cosimulation control structure.

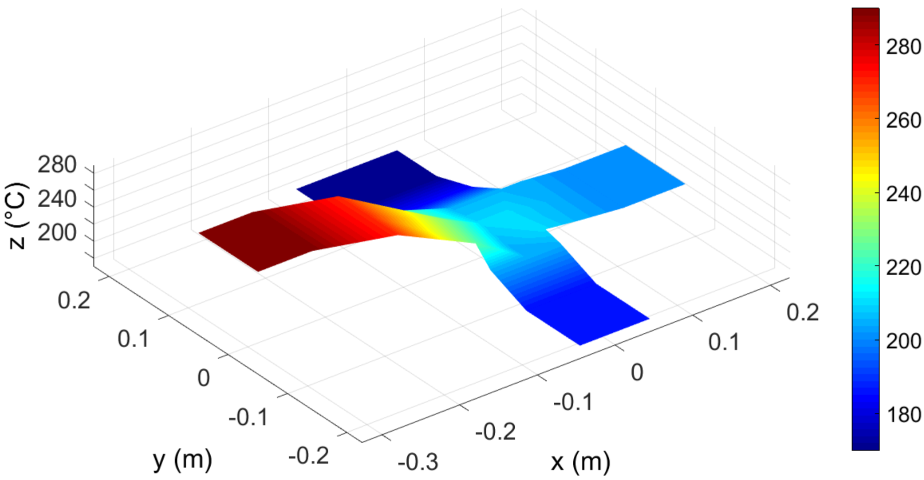


Fig. 14. Reference temperature field.

6 COSIMULATION CONTROL STRUCTURE

Cosimulation control structure is based on cooperation of software environments MATLAB & Simulink with advanced library DPS Blockset and COMSOL Multiphysics. Advanced component of COMSOL Multiphysics is COMSOL with MATLAB that makes the cooperation possible. In default control scheme as shows Fig. 13 occurs a problem of inaccurate settings of the controllers parameters and to achieve the highest precision it is necessary get inside HLDS block a convolution model of modeled system as perfect as possible. Thermal systems are characterized in particular by as the temperature is raising they change their physical properties and also ratio of heat transfer and conduction. Therefore if it is wanted to acquire the highest possible precision of the model there are several options. One is dynamics segmentation, where more than one convolution models are required. With these models effort is always to capture with one convolution model that field of temperatures, where the physical parameters are minimally changing, however 100% precision is not achieved only get slowly close to it by this method.

Second way that gives solution thanks to development of modern informatics technologies and software tools it is possible to replace convolution model directly by model in software for example COMSOL Multiphysics, Fig. 15.

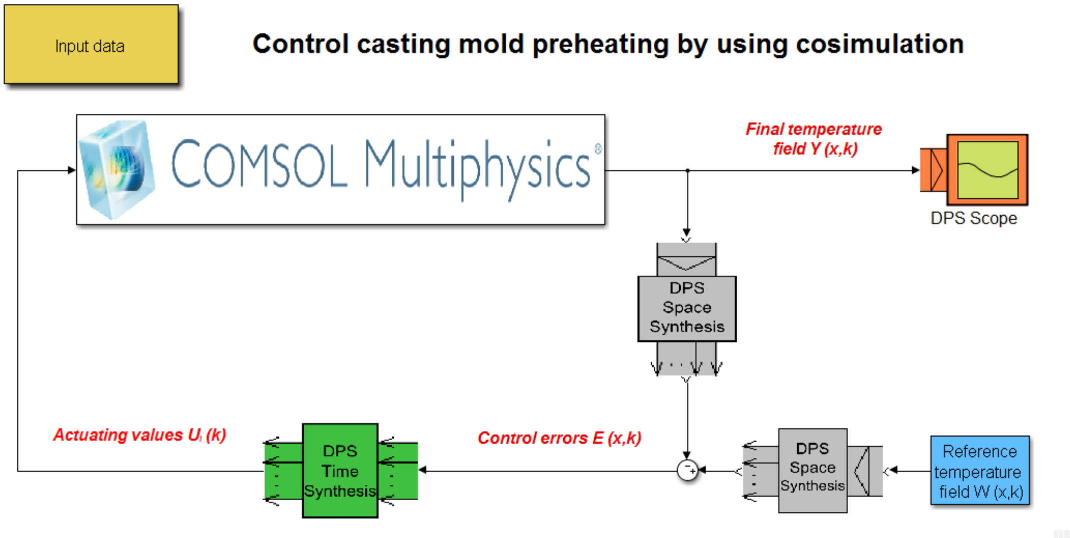


Fig. 15. Cosimulation control structure using DPS Blockset.

As it is seen Fig. 15 is largely identical as Fig. 13, the only difference is the replacement of convolution model by block securing communication between programs MATLAB & Simulink and COMSOL Multiphysics as well as data preparation for the correct registration into COMSOL Multiphysics before executing the computation process. Both control schemes are based on theoretical knowledge listed in the introduction of the paper. Thus the convolution model replacement right by model in COMSOL Multiphysics so the model accuracy reaches almost 100% when validated model can achieve a maximum precision.

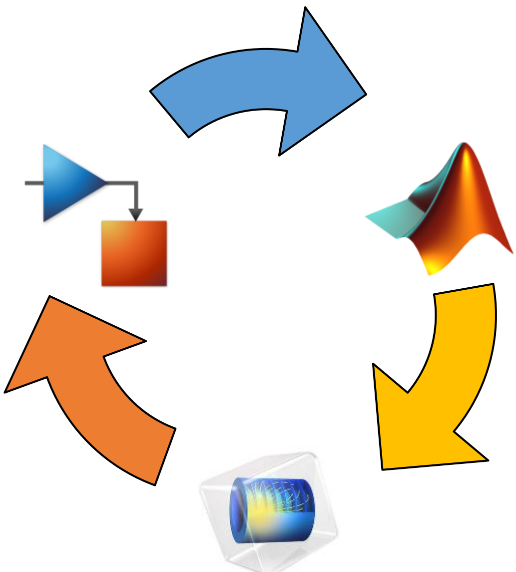


Fig. 16. Graphic interpretation of cosimulation functionality.

Cosimulation works in more steps. The first is load the data into the COMSOL Multiphysics environment that are prepared in proper format beforehand in cosimulation structure in MATLAB & Simulink software. In the case of casting mold preheating it is in form of power values and their attributes are afterwards written into the model, what is ensured by function developed in the software environment MATLAB. The second step of cosimulation is to run shor lasting simulation in COMSOL Multiphysics, executes by function that task was eve the writing the parameters to the model. The third step starts after the short simulation, length is identic to sampling time, the result of the simulation is recorded on the output of the function and represents the output quantity Y(x,k). First three steps are repeating in cycle with frequency of sampling time, Fig. 16, 30 seconds in demonstrative example. First cosimulation cycle come from defined initial conditions, linking the software environments allows to initial conditions be defined by function and it is not necessary to have for every operating point extra model. Each next cycle in the row does not come from first initial conditions but from temperature field finished calculation of last cycle, i.e. continues in simulation with modified input data which difference were solved in control section of cosimulation scheme. Replacement of convolution model by model in COMSOL Multiphysics is the result of this steps.

CONCLUSIONS

Final steady-state temperature field after control procession is in Fig. 17, temperature field is only one. Control structures, simulation scheme, Fig. 13, and structure using cosimulation, Fig. 15, gives identical output, therefore result steady-state temperature field is represented by both structures. Acquired steady-state temperature field succeed a high correspondence with reference temperature field, thus can be said the control schemes work correctly. Additional reason of this statement is that the temperature field at the end of control process have the required parameter to start casting. This parameter is raising gradient of temperature from the ending of the frameworks to the center of the mold, and from the center to the direction of the feeder, which is fulfilled and thereby technological demand for preheating of the casting mold is met as well.

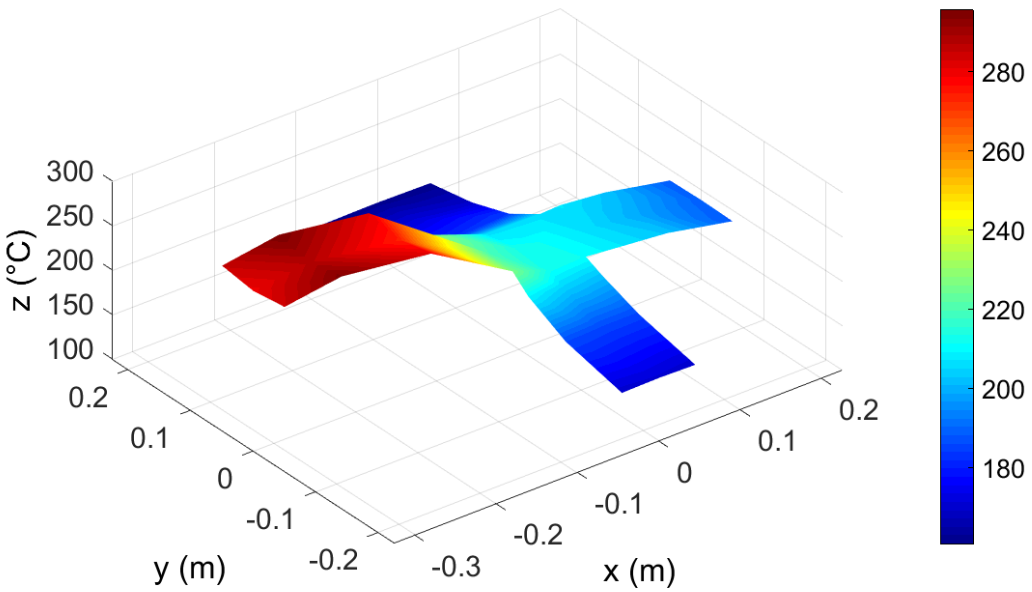


Fig. 17. Steady-state temperature field at the end of casting mold preheating.

Possible comparison of the results of the simulation and cosimulation control structure is shown in Fig. 18 where is the temperature transition in time at chosen thermocouple probes. These transitions show the equality of the steady-states between the structures, i.e. steady-state temperature field, Fig. 17, correctly represents steady-state both of the structures. On time responses can be seen the difference in sloped start part that is caused by convolution model, which was created on the base of step response characteristics defining the casting mold dynamics for given input signal. The change of physical characteristics and ratios of the heat transfer and conduction influence missed in convolution model is the origin of visible deviation during the slope start.

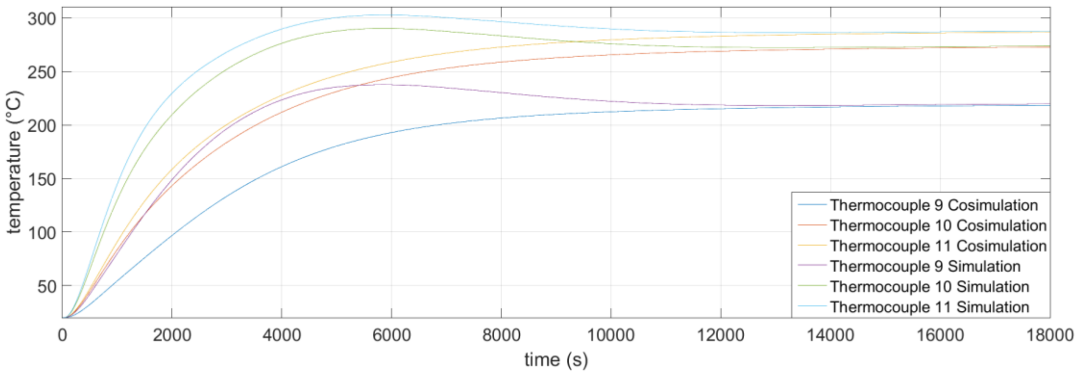


Fig. 18. Temperature transition at chosen thermocouples throughout casting mold preheating.

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