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PLC Control of Casting Die Preheating Process as Distributed Parameter System

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Abstract—In the paper a problem of casting die preheating control is solved. Concept of the control is designed based on distributed parameters systems. The design of the control structures are created within simulation studies, afterwards are connected into co-simulation regime network to tune the control parameters and then applied to control of preheating using PLC.

Keywords: preheating, co-simulation, distributed parameter system, DPS Blockset, control, PLC.

I. Introduction

Physical model of casting die in shape of a cross, Fig. 1, was constructed in the Institute of Automation, Measurement and Applied Informatics, Faculty of Mechanical Engineering, Slovak University of Technology in Bratislava, for analyzing modelling and control problems in field of gravity casting. Thermal knot of the die with complicated shape shows tendency to form draws and defects. The model offers mold preheating options to achieve fault-free casts. The mold preheating in the paper is formulated and solved as control task of distributed parameters system (DPS). Numerical model of the die is composed, distributed dynamic characteristics are examined and control system optimization is proceeded. In the end the optimized control system is implemented, making use of measurements of the temperature field at selected points of the mold, using PLC system with low processing power, which is commonly used in industrial practice.

II. The Dynamics and The Control Task for PLC

The casting technology is a typical case of the DPS. The time-space coupled nature of the DPS is described by partial differential equations (PDE) as infinite-dimensional systems [1]. Variety of transfer functions for systems described by PDE is illustrated by means of several examples in [2]. DPS are in engineering practice very frequently found in the form of lumped input and distributed parameter output systems (LDS), [3, 4].

In the case of preheating the mold actuating variables are given as supplied powers of each heating zone and controlled variable is the temperature field. It is generally a nonlinear lumped input and distributed parameter output system, which dynamics in linearized neighborhoods of chosen steady-states is modelled using discrete LDS with zero order hold units - HLDS as a controlled system of a discrete control loop - with discrete lumped input quantities and distributed parameter output quantity, Fig. 2.

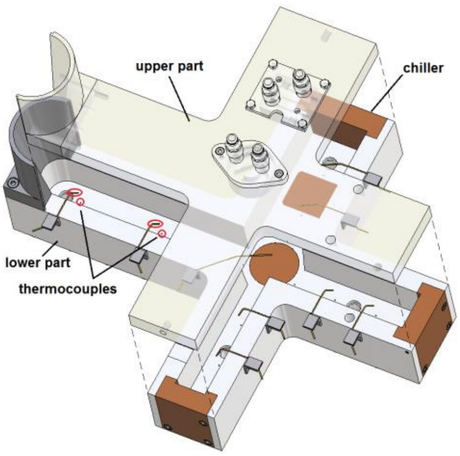

Fig. 1. Experimental casting die with embedded sensors and actuators

Fig. 2. Lumped input and distributed parameter output system with zero order hold units $\{U_i(k)\}_{i=1,5}$

Between discrete lumped inputs $\{U_i(k)\}_{i=1,5}$ and distributed output $Y(\boldsymbol{x},k)=Y(x,y,z,k)$, respectively particular distributed outputs $\{Y_i(\boldsymbol{x},k)=Y_i(x,y,z,k)\}_{i=1,5}$, the HLDS is defined by relation

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

where $\{\mathcal{G}H_i(\boldsymbol{x},k)\}_{i=1,5}$ are distributed impulse characteristics and $\oplus$ is the symbol of discrete convolution. During gradual effect of individual step changes on the side of inputs are obtained distributed transient characteristics $\{\mathcal{H}H_i(\boldsymbol{x},k)\}_{i=1,5}$ that at points $\{\boldsymbol{x}_i\}_{i=1,5}$ attain in steady-states their maximum amplitudes. To distributed transient characteristics in steady-states assigning their reduced transitions

$$\{\mathcal{H}HR_i(\boldsymbol{x},\infty)=\mathcal{H}H_i(\boldsymbol{x},\infty)/\mathcal{H}H_i(\boldsymbol{x}_i,\infty)\}_{i=1,5} \qquad (2)$$

for $\{\mathcal{H}H_i(\boldsymbol{x}_i,k)\neq 0\}_{i=1,5}$ accordingly assign to particular distributed output quantities their reduced transitions

$$\left\{YR_i\left(\boldsymbol{x},k\right)=Y_i\left(\boldsymbol{x},k\right)/Y_i\left(\boldsymbol{x}_i,k\right)\right\}_{i=1,5} \quad (3)$$

for $\left\{Y_i\left(\boldsymbol{x}_i,k\right)\neq 0\right\}_{i=1,5}$ afterwards on output

$$Y(\boldsymbol{x},k)=\sum_1^5 Y_i(\boldsymbol{x},k)=\sum_1^5 Y_i(\boldsymbol{x}_i,k)YR_i(\boldsymbol{x},k) \quad (4)$$

Further transfer functions $\left\{SH_i\left(\boldsymbol{x}_i,\mathrm{z}\right)\right\}_{i=1,5}$ are assigned to characteristics $\left\{\mathcal{G}H_i\left(\boldsymbol{x}_i,k\right)\right\}_{i=1,5}$. For $k\to\infty$ follows

$$\left\{\begin{array}{l} YR_i\left(\boldsymbol{x},\infty\right)=Y_i\left(\boldsymbol{x},\infty\right)/Y_i\left(\boldsymbol{x}_i,\infty\right)= \\ =U_i\left(\infty\right)\mathcal{H}H_i\left(\boldsymbol{x},\infty\right)/U_i\left(\infty\right)\mathcal{H}H_i\left(\boldsymbol{x}_i,\infty\right)= \\ =\mathcal{H}HR_i\left(\boldsymbol{x},\infty\right)\end{array}\right\}_i \quad (5)$$

In terms of the relation (4) holds between vector of particular distributed quantities $\bar{Y}_i\left(\boldsymbol{x}_i,k\right)=\left\{Y_i\left(\boldsymbol{x}_i,k\right)\right\}_{i=1,5}$ and vector of (measurable) components of distributed output quantity $\bar{Y}_i\left(\boldsymbol{x}_i,k\right)=\left\{Y_i\left(\boldsymbol{x}_i,k\right)\right\}_{i=1,5}$ in points $\left\{\boldsymbol{x}_i\right\}_{i=1,5}$ relation is given

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

Near steady state for $k\to\infty$ the output quantities $\left\{YR_i\left(\boldsymbol{x},k\right)\right\}_{i=1,5}$ converge to the courses of $\left\{\mathcal{H}HR_i\left(\boldsymbol{x},\infty\right)\right\}_{i=1,5}$, by the relation (5), therefore for calculation of values $\bar{Y}\left(\boldsymbol{x}_i,k\right)$ based on the $\bar{Y}\left(\boldsymbol{x}_i,k\right)$ can be considered with an approximate relation

$$\begin{bmatrix} Y\left(\boldsymbol{x}_1,k\right) \\ \vdots \\ Y\left(\boldsymbol{x}_i,k\right) \\ \vdots \\ Y\left(\boldsymbol{x}_5,k\right)\end{bmatrix}\doteq\begin{bmatrix} \mathcal{H}HR_1\left(\boldsymbol{x}_1,\infty\right),...,\mathcal{H}HR_5\left(\boldsymbol{x}_1,\infty\right) \\ \\ \mathcal{H}HR_1\left(\boldsymbol{x}_i,\infty\right),...,\mathcal{H}HR_5\left(\boldsymbol{x}_i,\infty\right) \\ \\ \mathcal{H}HR_1\left(\boldsymbol{x}_5,\infty\right),...,\mathcal{H}HR_5\left(\boldsymbol{x}_5,\infty\right)\end{bmatrix}\begin{bmatrix} Y_1\left(\boldsymbol{x}_1,k\right) \\ \vdots \\ Y_i\left(\boldsymbol{x}_i,k\right) \\ \vdots \\ Y_5\left(\boldsymbol{x}_5,k\right)\end{bmatrix} \quad (7)$$

and in abridged form of

$$\bar{Y}\left(\boldsymbol{x}_i,k\right)\doteq\bar{\mathcal{H}HR}_i\left(\boldsymbol{x}_j,\infty\right)\bar{Y}_i\left(\boldsymbol{x}_i,k\right) \quad (8)$$

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

$$\bar{Y}_i\left(\boldsymbol{x}_i,k\right)\doteq\bar{\mathcal{H}HR}_i\left(\boldsymbol{x}_j,\infty\right)^{-1}\bar{Y}\left(\boldsymbol{x}_i,k\right) \quad (9)$$

In terms of introduced characteristics

$$Y(\boldsymbol{x},\infty)=\sum_1^5 Y_i(\boldsymbol{x},\infty)=\sum_1^5 Y_i(\boldsymbol{x}_i,\infty)\mathcal{H}HR_i(\boldsymbol{x},\infty) \quad (10)$$

Control task in steady-state is to ensure the control error

$$E\left(\boldsymbol{x},\infty\right)=W\left(\boldsymbol{x},\infty\right)-Y\left(\boldsymbol{x},\infty\right) \quad (11)$$

between distributed output quantity $Y\left(\boldsymbol{x},\infty\right)$ and required quantity $W\left(\boldsymbol{x},\infty\right)$ in form of quadratic norm reaches its minimal value. Solution of approximation task for required quantity $W\left(\boldsymbol{x},\infty\right)$

$$\begin{aligned}\min&\left\|W\left(\boldsymbol{x},\infty\right)-\sum_{i=1}^n W_i\left(\boldsymbol{x}_i,\infty\right)\mathcal{H}HR_i\left(\boldsymbol{x},\infty\right)\right\|_2= \\ =&\left\|W\left(\boldsymbol{x},\infty\right)-\sum_{i=1}^n \breve{W}_i\left(\boldsymbol{x}_i,\infty\right)\mathcal{H}HR_i\left(\boldsymbol{x},\infty\right)\right\|_2\end{aligned} \quad (12)$$

is to assign vector $\bar{\breve{W}}_i\left(\boldsymbol{x}_i,\infty\right)=\left\{\breve{W}_i\left(\boldsymbol{x}_i,\infty\right)\right\}_{i=1,5}$ which in standard conditions of approximation task solution provides existence and explicitness of the best approximation within deviation approximation with minimal norm.

In the control process, while in term of equation (9) transient $\bar{Y}_i\left(\boldsymbol{x}_i,k\right)$ is calculated based on $\bar{Y}\left(\boldsymbol{x}_i,k\right)$ and in steady-state for $k\to\infty$ $\bar{Y}_i\left(\boldsymbol{x}_i,k\right)\to\bar{\breve{W}}_i\left(\boldsymbol{x}_i,\infty\right)$ then control error is equal to approximation deviation (12) with minimal norm, which means even distributed control error (11) in quadratic norm is minimal.

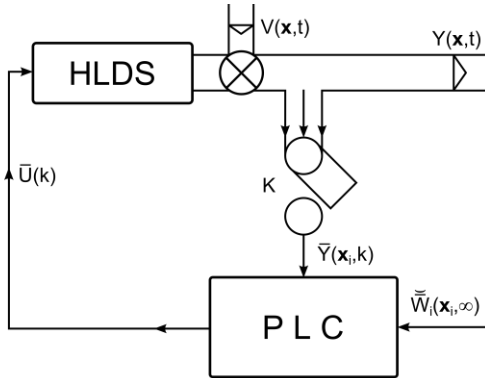

Fig. 3. Control system on PLC platform in linearized surroundings of steady state: $Y\left(\boldsymbol{x},t\right)$ – overall continuous distributed output quantity (temperature field), $\bar{Y}\left(\boldsymbol{x}_i,k\right)=\left\{Y\left(\boldsymbol{x}_i,k\right)\right\}_{i=1,5}$ – vector of lumped output quantities in selected points, $\bar{\breve{W}}_i\left(\boldsymbol{x}_i,\infty\right)=\left\{\breve{W}_i\left(\boldsymbol{x}_i,\infty\right)\right\}_{i=1,5}$ – vector of lumped reference/desired quantities in selected points in steady state, $\bar{U}\left(k\right)=\left\{U_i\left(k\right)\right\}_{i=1,5}$ – vector of lumped actuating quantities (electric powers), $V\left(\boldsymbol{x},t\right)$ – distributed disturbance quantity, K – sampling

Based on vector of distributed output quantities $\bar{Y}\left(\boldsymbol{x}_i,k\right)=\left\{Y\left(\boldsymbol{x}_i,k\right)\right\}_{i=1,5}$ in points $\left\{\boldsymbol{x}_i\right\}_{i=1,5}$ in Fig. 3 vector $\bar{Y}_i\left(\boldsymbol{x}_i,k\right)=\left\{Y_i\left(\boldsymbol{x}_i,k\right)\right\}_{i=1,5}$ is calculated by means of relation (9) on level of particular distributed output quantities. Vector $\bar{\breve{W}}_i\left(\boldsymbol{x}_i,\infty\right)$ is assigned to given distributed reference quantity, equation (12). Relation between vector components $\bar{U}\left(k\right)=\left\{U_i\left(k\right)\right\}_{i=1,5}$ and $\bar{Y}\left(\boldsymbol{x}_i,k\right)=\left\{Y\left(\boldsymbol{x}_i,k\right)\right\}_{i=1,5}$ is given by transfer functions $\left\{SH_i\left(\boldsymbol{x}_i,\mathrm{z}\right)\right\}_{i=1,5}$. Then controllers

$\{R_i(z)\}_{i=1,5}$ in control synthesis on PLC level are designed within single-parameters control loops, Fig. 4.

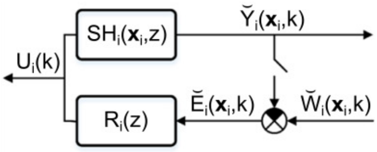

Fig. 4. i-th control loop for tuning controller $R_i(z)$

In control process under entered distributed reference quantity $W(\boldsymbol{x},\infty)$ based on relation (12) vector of reference quantities $\breve{\bar{W}}_i(\boldsymbol{x}_i,\infty)$ is computed. Result of the control process in final steady-state $\bar{Y}(\boldsymbol{x}_i,\infty)=\breve{\bar{W}}_i(\boldsymbol{x}_i,\infty)$ which means in terms of equation (11) the distributed control error $E(\boldsymbol{x},\infty)$ obtain its minimal value in quadratic norm, [5, 6].

III. Identification of Dynamics

To identify the dynamics of preheating of the casting die was needed to begin with importing CAD model of the casting die into COMSOL Multiphysics software. Afterwards boundary and initial conditions have been defined along with heat transfers between individual parts of the mold. Heating elements have been defined into five heating zones accordingly by real construction of the casting die. COMSOL Multiphysics environment is a program that uses finite elements method, for that reason mesh was created on imported model for calculation needs, Fig. 5. During verification of numerical model a specific measurements have been made at different operational modes and distributed transient characteristics $\{\mathcal{H}H_i(\boldsymbol{x},\mathrm{k})\}_{i=1,5}$ have been obtained.

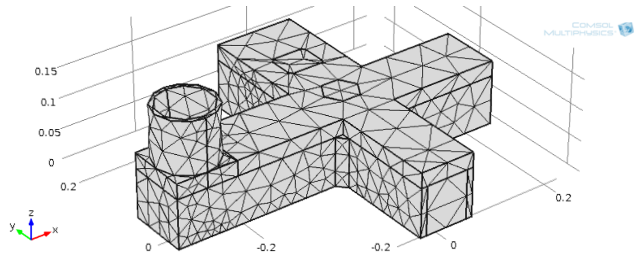

Fig. 5. Computing mesh of the casting die by finite elements method

Distribution of temperatures in the casting die over the definition domain $\Omega \in E_3$ for lumped input v quantities $\{U_i(\bar{x},t)\}_{i=1,5}$ in the form of heat sources (W/m^3) is modelled by PDE of parabolic type with initial condition and boundary conditions (BC) for heat flux:

$$\frac{\partial T(\bar{x},t)}{\partial t} - a\nabla^2 T(\bar{x},t) = \sum_{i=1}^{5} U_i(\bar{x},t)$$
$$-\mathrm{n}(-\lambda \nabla T) = h(T_{ext}-T) \qquad (13)$$
$$T(\bar{x},0) = T_{init}$$

where $a=\lambda/(\rho C_p)$ is temperature conductivity (m^2.s^{-1}).

The verification of the numerical model was performed via measurements at various operating modes and distributed step responses $\{\mathcal{H}H_i(\boldsymbol{x},\mathrm{k})\}_{i=1,5}$ were obtained.

For identification needs the transient characteristic with fastest dynamics had to be selected among the others. The fastest dynamic is chosen because it is best for representation of the heating dynamics of given zine. In Fig. 6 can be seen steady-state temperature field after simulation of heating unit step change in 4th heating zone.

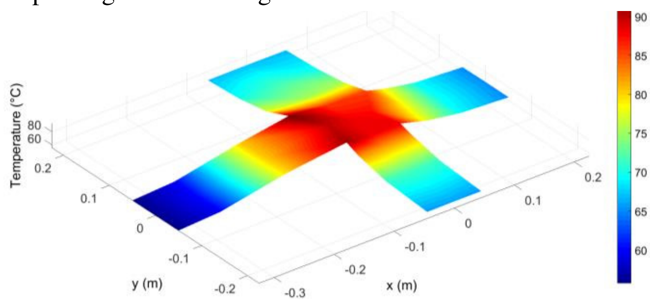

Fig. 6. Steady-state temperature field in 4th partial distributed transient characteristic

Identification of thermocouples with the fastest dynamics and transfer functions assigned to them can be seen in [7]. In identification process besides identifying system dynamics also static identification has been carried out, [8, 9]. Static characteristics are composed of points of steady-state temperatures from thermocouples with the fastest dynamics at the end of preheating simulation after changes of the input signal by 10% of nominal power of given zone. These static characteristics make for determination of temperature ranges, in which the casting die behaves nearly like linear system and on the other hand temperature ranges, in which slight nonlinearity of the mold occurs at low temperatures in its each zone. Based on found static characteristics temperature points were chosen where in their neighborhood weighting function is applied at parameters change of the controllers. The reason of choosing controllers with parameters change was made on basis of diversity of desired temperature field entered even by ordinary person who does not have knowledge in given problematic field. If the desired temperature field would be placed always out of nonlinear area then it would be possible overpass this area with constantly defined power in heating zones of casting die.

IV. Implementation of Control System to the PLC Platform

1) Initial preparation of implementation.

Initializing the control algorithm begun in simulation environment MATLAB & Simulink using extending product DPS Blockset, [10]. This Initial preparation can be found in [7]. Initialization of control algorithm in listed article deals also with possibility of dynamics decomposition. Controllers with changing parameters were applied in the next step.

2) Preparation of the implementation.

Within preparation of control algorithm was necessary to get as close to the real device of casting die as possible. To prevent possible differences in change of parameters of casting die (parameters are subject of temperature that brings nonlinearity into the system) an inter-step was performed, and by that co-simulation of softwares COMSOL Multiphysics and MATLAB & Simulink was carried out. Inside simulation environment during use of block HLDS from DPS Blockset was possible to have convolution model derived only from one regime of its creation and it is not possible with its help represent behavior changes of casting die at temperature changes, which it does not include. Hereby convolution model was replaced by model inside COMSOL Multiphysics directly.

In Fig. 7 can be seen desired temperature field that was identical to the one from co-simulation and also for application to PLC. Desired temperature field has a shape requested by technology, which comes from the direction of cast solidification and so the direction of temperature gradient has to be insured, [11]. Temperature gradient has to rise in direction from the ends of the frames to the center and forth from here to the feeder. Based on theory mentioned above, it is possible given temperature field define only in few chosen points, these points are identified fastest dynamics in given zones of casting die. By defining of temperature field in chosen points is achieved its best approximation using matrix inversion of space synthesis in space part of control algorithm.

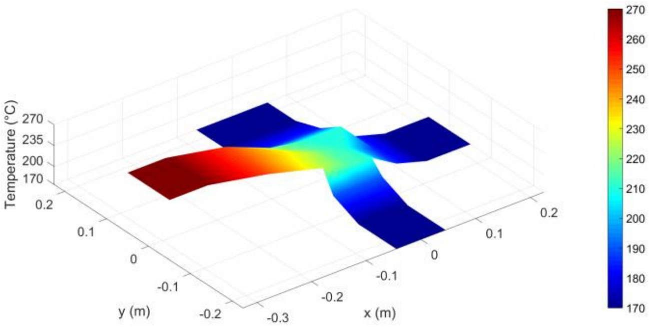

Fig. 7. Reference quantities (desired temperature field)

Co-simulation has several steps, as first step it is to load the data into COMSOL Multiphysics software, whose have to be prepared beforehand in required format, their preparation is done in co-simulation schema in Simulink. In case of preheating of casting die it is in form of power values in the zones, and their values are afterwards in the first step written into the model, what secures with help of function developed in MATLAB software. As manipulated input from controllers is in electrical form 0 – 10 V it is necessary to transform it to power in Watts. Second step of co-simulation is activate short simulation in environment COMSOL Multiphysics, activation is carried out by function, which task is also to write the parameters into the model. Third step runs after short simulation, the length of simulation is equal with sampling time, and result of simulation is written on output of the function and it represents output quantity $Y(\boldsymbol{x},k)$. The first to the third step is repeated cyclical with frequency of sampling time, in the paper sampling time of 5 seconds is used. Chosen sampling time length is adequate for this system. The first co-simulation cycle starts from defined initial conditions, thanks to joining of softwares can initial conditions be defined by function and there is no need to have model individually for every operating point. Every next cycle in order does not start from first initial conditions but from temperature field of previous cycle finished computation, i.e. continues in simulation with new input data that change was solved in control part of co-simulation schema. The replacement of convolution model by model in environment COMSOL Multiphysics was achieved by this.

Schema of time – space control structure is shown in Fig. 8. In this structure convolution model in HLDS block from DPS Blockset was replaced by connection to model of casting die in COMSOL Multiphysics environment. Convolution model was premade for manipulated input from time component of the control in form of 0 – 10 V, however model in COMSOL Multiphysics runs with inputs based on entered power, for that reason voltage signal is recalculated to value in Watts. As output quantity $Y(\boldsymbol{x},k)$ is vector representing whole temperature field, Fig. 14, though the control proceeds on measurement principle only in chosen points and therefore is required to choose from output quantity only points in places of thermocouples with identified fastest dynamics.

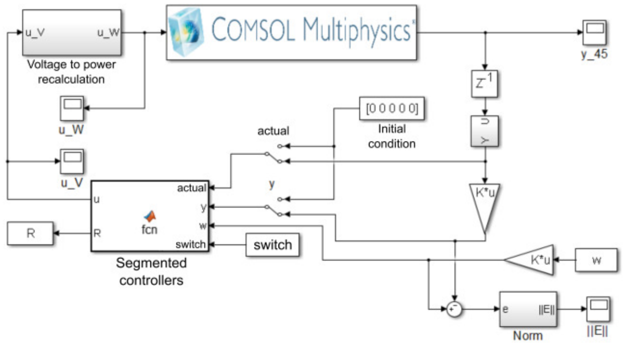

Fig. 8. Control loop with using co-simulation

The space part of the control is carried out using matrix inversion as it is described in theory section of the paper. The time component of the control is composed of set of 5 segmented controllers. Each controllers set is made of two separated PI controllers and weighting function, which secures gradual change of the parameters from one to second PI controller. This function is applied in neighborhood of the biggest nonlinearity found from static characteristics. As there are two blocks with functions inside placed in the schema it is necessary before starting the initialization to create these functions by initial condition so the build process of the schema in Simulink worked out properly without errors.

3) Implementation.

To implement the control schemas into PLC system the option of joining the software MATLAB & Simulink with Automation Studio was used. For connection of these two software products it is required to install extension B&R Automation Studio Target for Simulink that allows afterwards to define single inputs and outputs of the system, also the schema configuration options. Before control schema creation it is needed to have project prepared in environment Automation Studio, in which the control schema will be implemented. The project must contain hardware configuration of PLC system and on a global level must have defined used variables with declared connection on input/output cards in hardware configuration.

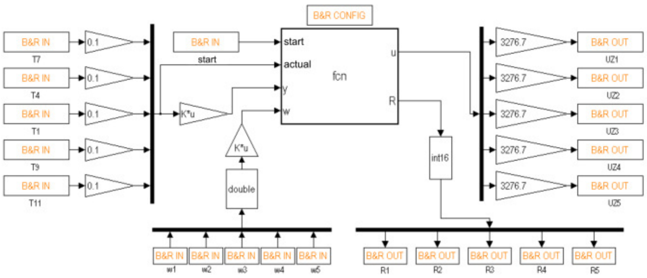

Fig. 9. Control loop on PLC platform

In Fig. 9 can be seen time – space control schema with segmentation of PI controllers prepared to be implemented in PLC. Block solving time control task has several inputs and outputs. The first input is sign as "start", here enters a variable that starts control task so then the control will not always start when the PLC turns on. The value of this variable is controlled through visualization environment. The second input belongs to the connection of actual temperature send into control algorithm. Actual temperature is needed by weighting function at PI controllers parameters gradual change. Last two inputs create output quantity and reference quantity in partial form. Reference quantity is entered by the user through visualization environment. The control error is computed inside time synthesis of the control. Considering that the measurement card gives out the temperature in one tenths of degree, it needs to be calculated into degrees of Celsius and reference value transform from data type integer to double. Data type change must be done on outputs as well, but for the second output that indicates status the controllers are in transform to integer is sufficient. The first output, manipulated output, recalculation from voltage signal to integer value and afterwards write the values in data type integer needs to be done. Next the schema using "coder" was retransformed into program language C and as one program implemented to structure of Automation Studio software, then from where was loaded to PLC system. With such premade time – space structure after control approach change only adjust time component of the control is enough and the rest of the structure also with variables stays unmodified. The matrix for inversion inside the space synthesis must be available before the implementation of the control schema.

Manipulation and control of the casting die by PLC offers the possibility to manipulate and control the casting die even to common person by means of visualization. Used PLC does not have visualization panel but is able to create and handling of visualizations through Ethernet network. PLC can be connected via VNC Viewer, thereafter to view displayed or insert requested parameters is possible. Now that the visualization exists the user does not need to know how to do programming of PLC and can control the whole technology as it works in industry.

In Fig. 10 is shown the visualization window belonging to automation control mode. This automation mode contains control with time – space schema from Fig. 9. On the model simulation parameters of reference temperature field are preset however the user can change them at will. Changing parameters is possible from temperature 20°C to maximum of 300°C. The maximum temperature have been chosen considering the physics of the casting die in order to prevent unnecessary wear of the material of the mold do not occurrence and from reason of vision of casting and melting of lead solder in the casting die body. While melting temperature of the lead solder is around up to 200°C, so maximum limit of 300°C is still a big reserve. Before the control starts there is the option to archive data the user chooses if the control process progress and result should be saved or not. Besides automation mode, the HMI environment has also the option of manual controlling the preheating power of casting die and power of the chillers as well.

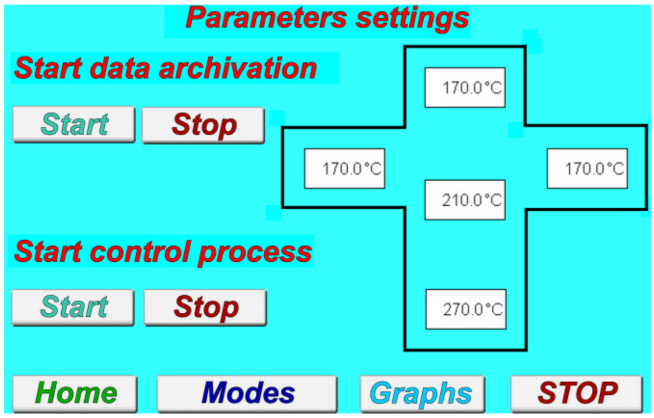

Fig. 10. HMI Configuration window

Conclusions

The paper presents the possibilities of preheating control of casting die as DPS by using PLC. The co-simulation is used between virtual software environments COMSOL Multiphysics and MATLAB & Simulink in cooperation with DPS Blockset for MATLAB & Simulink.

In Fig. 11 and Fig. 14 are shown the results as evaluation interpretation of the simulation. In Fig. 11 can be seen the temperature transients from all thermocouples during control process. The temperature values registration is made by program in PLC. As it is seen from the transients the control task is realized with minimal deviation of quadratic norm, Fig. 12. Given transients are corresponding to segmented controllers application in time component of the control.

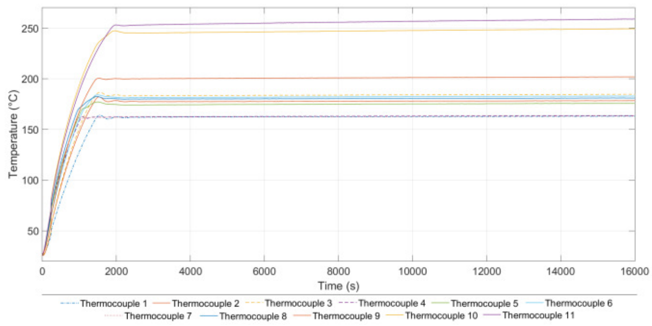

Fig. 11. Control process transients of the casting die using PLC

Fig. 13 shows how was weighting function used within control process, i.e. when the gradual change of the parameters of the controllers has been occurring.

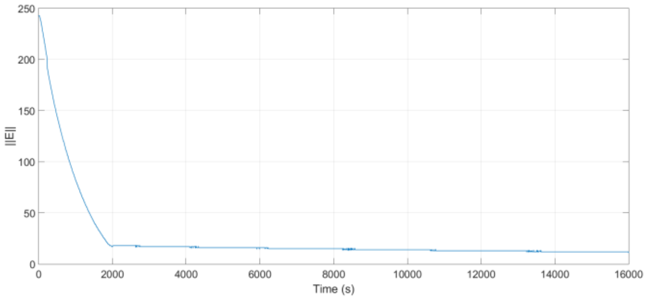

Fig. 12. Quadratic norm of the control process

If the parameter is equal 1 then PI controller works with constant values of the first set, in case of it is equal to 2, the weighting function is used for gradual change of the parameters of the PI controller and in the last case if it is equal to 3 then only constant values of the second set of the PI controller are used. Constant values of the first set are adjust to advance closer to the reference quantity more aggressively as it is for the constant values of the second set.

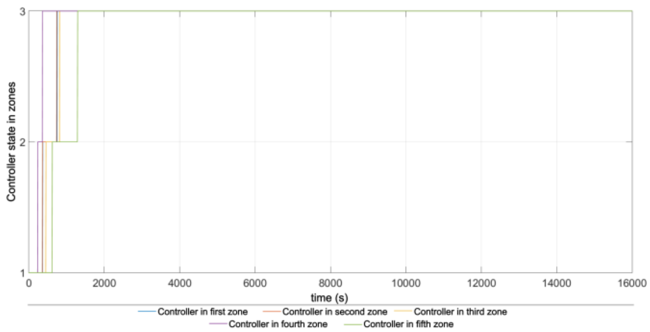

Fig. 13. Weighting function application on the controllers

In concept of co-simulation is its result as close to the real experiment result as accurate is model in COMSOL Multiphysics software. Within preparations the model was verified by the real device. For that reason final temperature field acquired from co-simulation corresponds also to the result of the real experiment. From the physical measurement it is not possible to get the result in the form of temperature field, because on the casting die the temperature is measured only in chosen points and not in entire field of definition, in contrast of co-simulation, where the result is received in entire field of definition thanks to the finite elements method, Fig. 14.

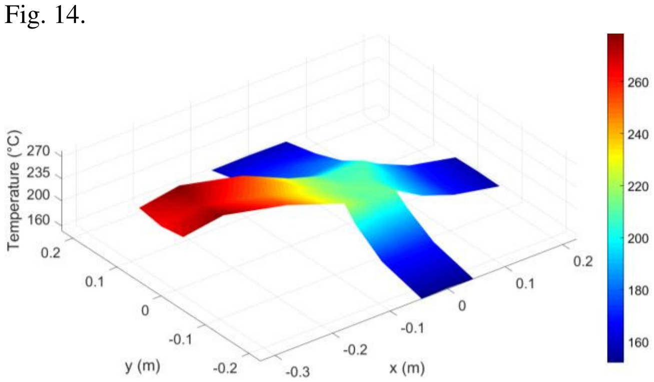

Fig. 14. Steady-state temperature field of casting die after control process

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References

[1] J. L. Lions, "Optimal control of systems governed by partial differential equations," Berlin, Heidelberg, New York: Springer-Verlag, 1971.

[2] R. Curtain and K. Morris, "Transfer functions of distributed parameter systems: A tutorial," Automatica 45, 2009, pp. 1101-1116.

[3] G. Hulkó, et al. "Modeling, control and design of distributed parameter systems with demonstrations in MATLAB," Publishing House of STU, Bratislava, pp. 265. 1998. ISBN80-227-1083-0.

[4] G. Hulkó, et al. "Engineering methods and software support for modelling and design of discrete-time control of distributed parameter systems," In: European Journal of Control. ISSN 0947-3580. Vol. 15, Iss. 3-4, Fundamental Issues in Control, pp. 407-417. 2009.

[5] G. Hulkó, C. Belavý, K. Noga and K. Ondrejkovič, "Control of technological and production processes as distributed parameter systems supported by virtual software environments," Publishing House of STU, Bratislava, pp. 283. 2015. ISBN 978-80-227-4289-4.

[6] G. Hulkó, "Control of DPS by means of multi-input and multi-distributed - output systems," In: Preprints of 10-th World Congress of IFAC, Munich. 1987.

[7] L. Bartalský, "Control of thermal regimes of intelligent casting die as distributed parameter system by PLC," PhD thesis, pp. 112. Bratislava. 2016.

[8] J. Vachálek, M. Bartko and J. Bizub, "Long-run on-line identification with hybrid regularized exponential forgetting method," In Proceedings of the 15th International Carpathian Control Conference: ICCC 2014; Velké Karlovice, Czech Republic: IEEE, CD-ROM, p. 635-640. ISBN 978-1-4799-3527-7.

[9] G. Takács, J. Vachálek and B. Rohaľ-Ilkiv, "Identification of systems," 1. ed. Bratislava STU 2014. 281 pgs., (in Slovak), ISBN 978-80-227-4288-7.

[10] G. Hulkó, et al. "Distributed parameter systems blockset for MATLAB & Simulink," DPS Blockset for MATLAB & Simulink. Bratislava – Natick, 2003-2013.

[11] A. Long, D. Thornhill, C. Armstrong and D. Watson, "The impact of die start-up procedure for high pressure die casting," SAE Int. J. Mater. Manf. 6(3):416-426, 2013.