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Compromising Controller Parameters Setting for a Delayed Thermal Process

Libor Pekař, Roman Prokop
Faculty of Applied Informatics
Tomas Bata University in Zlín
Zlín, Czech Republic
{pekar, prokop}@fai.utb.cz

Abstract— **The primary goal of this contribution is to present an original idea of a suboptimal controller parameters setting that intends to achieve a compromise between various requirements on the control response performance. Performance (quality) measures include integral and absolute criteria. The idea is demonstrated and applied to a robust control of a thermal process that shows internal delays. As the subsidiary objective, the reader is acquainted with a concise summary of the robust control design for the delayed model based on the algebraic principle over a special ring. The obtained results are demonstrated not only by means of computer simulations but via laboratory measurements as well.**

Keywords—controller tuning; robust control; time-delay system; thermal process

I. Introduction

Thermal systems and processes with heat exchangers are employed in a wide range of human activities, for instance in energetic, metallurgical or chemical industry [1], [2]. Plenty of control strategies for this family of systems have been developed and implemented to improve the overall control response during recent decades, see e.g. [3]-[5] and references therein, to introduce just a few. They cover optimal, adaptive, robust, artificial intelligence, nonlinear and many other control principles.

Processes, plants and networks with heating and cooling elements and heat exchangers with an in-loop circulating medium constitute a significant subset of this systems family. Their modeling, analysis and control is a nontrivial task because of their complex dynamics due to nonlinearity, distributed or delay caused by the aftereffect phenomenon of the closed circulation. A possible modeling of such systems can be made according to the anisochronic principle [6], [7] which is utilized in this contribution. A generalized model-predictive control (MPC) method with disturbance measurement was proposed in [8]. Robust MPC ideas were used by Bakošová and Oravec [9] and improved and extended when controlling a heating-cooling networked system in [10]. Predictive control methods with artificial neural networks (ANNs) for a system with a heat exchanger and input delays were compared in [4]. In [11], the combination of the ANN and MPC was designed for a class of nonlinear systems with constant input and internal delays. The polynomial linear-quadratic control design approach incorporating the digital Smith predictor was implemented by Bobál et al. [12]. Recently, we have applied robustness principles to a laboratory heating-cooling process with long internal delays [13].

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Most of these principles concern controller structure determination, or (if it is apriori known) the eventual acceptable controller parameter values are within ranges satisfying particular control performance conditions or they are not explicitly known, or the parameter determination is restricted to the searching of optimal cost function or ANN's parameterization. This contribution is primarily aimed at the introduction of a controller parameters setting based on the evaluation of a multi-criterial decision-making task, when controlling a laboratory thermal process with significant input and internal delays. Before this decision, parameter values sets are found by the application of elementary robust stability and robust performance ideas and principles. Note that the studied appliance has been utilized to verify and validate several control methodologies, see e.g. [8], [12]. Modelling and identification of the process were completely introduced in [7], and the overall robust controller structure design can be found in [13]. This paper, in fact, intends the reader to be acquainted with the broad summary of these results as the secondary aim. The latter reference also includes a very concise description of the controller tuning principle herein presented; hence, this contribution extends and summarizes these ideas.

The rest of paper is organized as follows: Algebraic tools and robustness rules giving rise to the controller structure are given to the reader in the preliminary Section 2. The main result – the compromising controller parameters setting - is presented in Section 3. A description of the laboratory appliance and its mathematical model follow by the complete concise control design are the objectives of Section 4, in which the presented ideas are verified by numerical (simulation) results as well as by real measurements. Then the paper is concluded.

II. Preliminaries

This section includes basic algebraic tools and rules and robustness essentials that are used to determine the structure of the eventual controller, to be tuned below, for the delayed heating-cooling process.

A. *Control Design in the R_{QM} Ring*

Let the controlled plant transfer function be in the form

$$G(s) = B(s)/A(s) \tag{1}$$

where $A(s)$, $B(s)$ are from the R_{QM} ring which has been defined in [14]. The ring is applicable to systems with input and/or internal (state) delays of retarded or even neutral type. Moreover, both terms in (1) are coprime, i.e. they do not have any common non-invertible element from R_{QM}.

Consider a control feedback system with a feasible controller governed by a coprime transfer function over R_{QM} and external inputs $r(t), d(t)$ expressing the reference signal and the load disturbance, respectively. Then the control system is stable (in the sense of the ring definition) if and only if

$$M(s) = 1 \tag{2}$$

where $M(s) \in R_{QM}$ is the characteristic term of the feedback system. For linear systems, condition (2) has the form of a linear Diophantine equation (Bézout identity), the solution of which can be further parameterized. By considering (2) and its parameterization, the reference is asymptotically tracked and the load disturbance attenuated if

$$\begin{aligned} G_{RE}(s)/F_R(s) &\in R_{QM} \\ G_{DY}(s)/F_D(s) &\in R_{QM} \end{aligned} \tag{3}$$

respectively, where $G_{RE}(s)$ expresses the transfer function of the reference to the control error ($e(t)$) and $G_{DY}(s)$ means that of the load disturbance to the output ($y(t)$). Functions $F_R(s)$ and $F_D(s)$ lying in R_{QM} stand for the denominator term of the factorized Laplace forms of $r(t)$ and $d(t)$, respectively.

B. Robustness Requirements and Conditions

In this paper, basic and well-known requirements on robust stability and performance are utilized for control design, the reader is referred e.g. to [15]. These principles can be, in general, formulated as follows. Let us denote nominal (unperturbed) functions with the subscript 0, the perturbed ones remain unsubscripted. The feedback system is robustly stable if

$$\sup_{\omega \geq 0} \left(|L(\mathrm{j}\omega)| - |L_0(\mathrm{j}\omega) + 1| \right) < 0 \tag{4}$$

where $L(s)$ is the open-loop transfer function. Robust performance means that (4) holds and the modulus of the (perturbed) sensitivity function $S(s) = G_{RE}(s)$ does not exceeded the prescribed weight function $W_P(s)$, i.e.

$$\| W_P(\mathrm{j}\omega) S(\mathrm{j}\omega) \|_\infty < 1 \tag{5}$$

III. COMPROMISING CONTROLLER PARAMETERS SETTING

Once the controller structure by means of (1)-(3) is derived, conditions (4), (5) together with the knowledge of dynamics of controlled process and external signals yield the determination of admissible parameter ranges. Hence, a further objective is to select particular values of controller parameters. This can be done e.g. by the introduction of an additional cost function or via simulation. Let us introduce a methodology incorporating and evaluating multiple criteria, so that a compromise between them is found.

Denote $k_i, i = 1,2,..N_k$ the set of tunable controller parameters, the values of which may lie within the corresponding interval sets $\lfloor k_{i,\min}, k_{i,\max} \rfloor$. The mean value of the interval and its length are $\bar{k}_i = 0.5(k_{i,\min.} + k_{i,\max})$ and $\langle k_i \rangle = k_{i,\max} - k_{i,\min.}$, respectively.

When solving a particular control task, there are various practical requirements on the performance. It is possible to include e.g. the maximum output overshoot, absolute and squared integrals of control error and the manipulated input, the influence of disturbances etc. into consideration. All these quantified measures express particular cost functions $f_j, j = 1,2,..N_f$ that are to be minimized. However, a consensual or compromising solution has to be found among all these cost functions.

Our simple idea is motivated by the endeavor to reduce the number of necessary computations to determine a sub-optimal solution. Moreover, it introduces dimensionless functions, so that all particular cost functions have initially the same impact to the overall cost. These functions also depends on dimensionless forms of controller parameters.

Hence, define dimensionless sensitivities $\Sigma_j(k_i)$ of measures $f_j(k_i)$ to the controller coefficients k_i as

$$\Sigma_j(k_{i,0}) = \frac{\Delta f_j(k_i)}{f_j(k_i)} \left(\frac{\Delta k_i}{k_i} \right)^{-1} \Bigg|_{k_i = k_{i,0}} \tag{6}$$

where $k_{i,0}$ stands for a particular value of k_i. Apparently, if $\mathrm{sgn}(\Sigma_j(k_i)) = 1$, the higher value of k_i yields the higher value of f_j, which means that the particular performance measure becomes worse. In other words, it is optimal to take a lower value of k_i, and vice versa. The value set $\Sigma_j(\bar{k}_i)$ for $i = 1,\ldots,N_k, j = 1,\ldots,N_f$ can be then applied to the determination of the eventual controller parameter values as

$$k_{i,\mathrm{fin}} = \bar{k}_i - 0.5\langle k_i \rangle \frac{\sum_{j=1}^{N_k} l_j \Sigma_j(\bar{k}_i)}{\sum_{j=1}^{N_k} l_j |\Sigma_j(\bar{k}_i)|} \tag{7}$$

where $l_i > 0$ mean weights that correspond to particular Σ_j. Notice that (7) gives natural results for both marginal cases. That is, if $\operatorname{sgn}(\Sigma_j(k_i)) = 1$ for all j, then $k_{i,\text{fin}} = k_{i,\min}$; contrariwise, if $\operatorname{sgn}(\Sigma_j(k_i)) = -1$ for all j, then $k_{i,\text{fin}} = k_{i,\max}$.

IV. Delayed Thermal Process Control - Example

This section is aimed at the application of the above introduced ideas, especially the controller tuning principle, to control an internally-delayed laboratory thermal process with the heat exchanger. Let us begin by a very concise appliance description and its mathematical model.

A. Controlled Plant and its Model

The physical model has four main parts that are connected by the piping, so that a heating medium (or a fluid) – water - circulates in a closed heating-cooling system: a through-flow heater, a long insulated pipeline, a cooler (air water heat exchanger) and a pump. Temperature of the outlet water flow from the heater, inside which the input power $P_{\mathrm{H}}(t)$ (W) acts, is measured by using a platinum resistance thermometer giving rise to the value of $\vartheta_{\mathrm{HO}}(t)$ (°C). The most significant transport delay is caused by that the hot water then goes through the long insulated coiled copper pipeline to the cooler. Here, two fans can blow air across the piping; the first one of is continuously controllable by $u_{\mathrm{C}}(t)$ (V), whereas the second one is of the on/off type and can be used only in emergency. Temperatures on the input and output of the heat exchanger are measured as $\vartheta_{\mathrm{CI}}(t)$ and $\vartheta_{\mathrm{CO}}(t)$ (°C), respectively. The fluid is transported by a magnetic drive centrifugal pump (placed behind the cooler), the power of which is continuously controlled by the input signal $u_{\mathrm{P}}(t)$ (°C). Finally, the pump output is closely connected to the heater input where the value of $\vartheta_{\mathrm{HI}}(t)$ is measured. The appliance communicates with a computer equipped with a data acquisition card and the Real-Time™ toolbox running in the Matlab® environment via a serial link. A scheme of the process is omitted here due to the limited space. A detailed description of the laboratory model can be found e.g. in [16].

The mathematic model utilized in this experiment has been obtained by means of the anisochronic modelling approach [6]. Basically, lumped dynamics of separate parts of the process are modeled by using heat balance and via algebraic relations experimentally acquired earlier, and then, these submodels are assembled and joined such that latencies between them are comprised. Due to the closed circuited nature of the process, these delays do not constitute purely input-output relations, but they partially appear on the left-hand sides of eventual differential equations, i.e. in the characteristic equation of the controlled system.

Once the parameterized model is obtained, unknown constants are to be determined. Here, the nominal model parameter values have been obtained in two basic steps. First, measured steady state input-output relations are used to find values of static parameters, except for delays, by the solution of the nonlinear least mean squares. As the second step, a dynamic response serves for the determination of masses in the model by the matching the measured transitional part of the step response to the modeled one by means of the least means squares criterion. Delays are graphically determined from the step responses as well. The reader is referred to [7] for the modelling and identification of the thermal process in more detail.

The first order Taylor series expansion at the steady operating point results in a 3x3 transfer function matrix for corresponding inputs $\Delta u_{\mathrm{P}}(t), \Delta u_{\mathrm{C}}(t), \Delta P_{\mathrm{H}}(t)$ and outputs $\Delta\vartheta_{\mathrm{HO}}(t), \Delta\vartheta_{\mathrm{CI}}(t), \Delta\vartheta_{\mathrm{CO}}(t)$ where Δ means the deviation from the operating point. Our intention is to control $\Delta\vartheta_{\mathrm{CO}}(t) = y(t)$ through $\Delta P_{\mathrm{H}}(t) = u(t)$, the relation of which can be given by the transfer function

$$G(s) = \frac{b_0 + b_{0D}\exp(-\tau_0 s)}{s^3 + a_2 s^2 + a_1 s + a_0 + a_{0D}\exp(-\tau_a s)}\exp(-\tau_b s) \quad (8)$$

with nominal values $b_0 = 2.05\cdot 10^{-7}$, $b_{0D} = 2.33\cdot 10^{-6}$, $a_0 = 1.41\cdot 10^{-4}$, $a_{0D} = 7.63\cdot 10^{-5}$, $a_1 = 8.99\cdot 10^{-2}$, $a_2 = 0.18$, $\tau_0 = 1.5$, $\tau_b = 141$, $\tau_a = 151$.

B. Controller Structure Design

Let us select the feedback control system with two feedback controllers; the first one with the transfer function $G_Q(s) = Q(s)/P(s)$ (where $Q(s), P(s) \in R_{QM}$ are coprime) is placed in the inner negative feedback loop, whereas the second one, $G_C(s) = C(s)/P(s)$, $C(s) \in R_{QM}$, is included in the outer negative feedback loop so that its input agrees with $e(t)$. The reader is referred e.g. to [13] for further details about the control system. The latter fraction is coprime again. The calculated control action $u_0(t)$ is then given by the difference of the outputs from $G_C(s)$ and $G_Q(s)$. The eventual plant input is supposed to be affected by the disturbance as $u(t) = u_0(t) + d(t)$. The reader is referred e.g. to [17] for details and the figure scheme.

We assume a linearwise reference signal, i.e. $F_R(s) = s^2$, and the load disturbance as a stepwise function, $F_D(s) = s$; see (3). In practice, a required gradual temperature growth or decline is much comfortable than an abrupt change in the reference. Nevertheless, it is usually sufficient to consider precipitous disturbance changes affecting the manipulated input. The laboratory measurement can be vitiated e.g. by an unexpectedly opened window or by a fast human movement. Under these assumptions, the following eventual controller transfer functions can be derived

$$\begin{aligned} G_Q(s) &= m_0^3 \frac{\left(s^3 + a_2 s^2 + a_1 s + a_0 + a_{0D}\exp(-\vartheta s)\right)(1-\gamma)\nu_1 s^2}{\left(p_4 s^4 + p_3 s^3 + p_2 s^2 + p_1(s)s + p_0(s)\right)(s + m_1)} \\ G_R(s) &= m_0^3 \left(\gamma_1 s^2 + (\nu_1 m_1 + \nu_0)s + \nu_0 m_1\right) \\ &\quad \frac{\left(s^3 + a_2 s^2 + a_1 s + a_0 + a_{0D}\exp(-\vartheta s)\right)}{\left(p_4 s^4 + p_3 s^3 + p_2 s^2 + p_1(s)s + p_0(s)\right)(s + m_1)} \end{aligned} \quad (9)$$

where

$$p_4 = (b_0 + b_{0D})^2, p_3 = 4m_0(b_0 + b_{0D})^2,$$
$$p_2 = 6m_0^2(b_0 + b_{0D})^2,$$
$$p_1(s) = m_0^3 \begin{pmatrix} 4(b_0 + b_{0D})^2 - (b_0 + b_{0D}\exp(-\tau_0 s)) \\ (b_0(m_0\tau + 4) + b_{0D}(m_0(\tau + \tau_0) + 4))\exp(-\tau s) \end{pmatrix}$$
$$p_0(s) = m_0^4(b_0 + b_{0D})\begin{pmatrix} b_0(1 - \exp(-\tau s)) \\ + b_{0D}(1 - \exp(-(\tau + \tau_0)s)) \end{pmatrix}$$
$$v_1 = b_0(m_0\tau + 4) + b_{0D}(m_0(\tau + \tau_0) + 4)$$
$$v_0 = m_0(b_0 + b_{0D})$$

Adjustable controllers' parameters, thus, read $m_0, m_1 > 0$ and $\gamma \in [0,1]$. The reader is referred to [17] for further details about the derivation of (9) and to [14] for general algebraic operations in R_{QM}.

C. Robustness Analysis

Basic results from robust stability and robust performance analysis are summarized in this subsection. There are multiple reasons for the application of robustness tools. To name just a few, significant measurement and model uncertainties appear when model parameters identification, voltage fluctuations and the limited sensor resolution influence measured output temperatures, there are unmodelled dynamics of heat-source, heat-consumption and mechanical parts, ambient temperature in the laboratory room varies during the year in the range from 18 to 28 °C, or hence, internal delays due to the fluid flow are not constant [13].

For the selected control system, conditions (4), (5) are expressed as

$$\left\| W_M(\mathrm{j}\omega)T_0(\mathrm{j}\omega)\left(1 + \frac{G_Q(\mathrm{j}\omega)}{G_R(\mathrm{j}\omega)}\right)\right\|_\infty < 1 \tag{10}$$

$$\left\| \begin{array}{l} \left| W_M(\mathrm{j}\omega)T_0(\mathrm{j}\omega)\left(1 + \frac{G_Q(\mathrm{j}\omega)}{G_R(\mathrm{j}\omega)}\right)\right| \\ + \left| W_P(\mathrm{j}\omega)\left(S_0(\mathrm{j}\omega) + W_M(\mathrm{j}\omega)T_0(\mathrm{j}\omega)\frac{G_Q(\mathrm{j}\omega)}{G_R(\mathrm{j}\omega)}\right)\right| \end{array} \right\|_\infty < 1 \tag{11}$$

see e.g. [17] for details again. The application of (10) results in the eventual range $m_0 \in (0, 0.055]$. To determine m_1, λ, let us initially select $\lambda \in [0.2, 0.8]$ and $m_1 \in [0.001, 0.009]$ in the accordance to process dynamics. Instead of a protracted numerical determination of the region in R_2 that satisfies (11), try to follow the idea described in Section 3 and consequently verify (11).

D. Parameters Determination

It can be deduced from the sets above that $\overline{m}_0 = 0.0275, \overline{m}_1 = 0.005, \overline{\gamma} = 0.5$ and $\langle m_0 \rangle = 0.0275$, $\langle m_1 \rangle = 0.004, \langle \gamma \rangle = 0.3$. There are naturally many ways how to handle the quality and the performance of control responses. Optimization criteria have to include both, minimum/maximum values of the corresponding signal as well as some integral values closely related to energy consumption. Hence, assume here the following measures: Denote $\delta e_{lc,\max}$, $\delta e_{cc,\max}$ as maximum relative overshoots of $y(t)$ immediately caused by a linear-to-constant transition of the reference and a constant-to-constant one, respectively, i.e.

$$\delta e_{\cdot,\max} := \max_{t \in [t_1, t_2]} \left| \frac{y(t) - r(t)}{r(t)} \right| = \max_{t \in [t_1, t_2]} \left| \frac{e(t)}{r(t)} \right| \tag{12}$$

for some suitable time instants t_1, t_2. Analogously, let the maximum relative output overshoot after a step change of $d(t)$ be $\delta e_{d,\max}$. For the same three output ranges, define integral absolute errors (IAEs) of the output responses caused by reference deviations and a load disturbance change (as introduced above) as $e_{lc,IAE}, e_{cc,IAE}, e_{d,IAE}$, respectively, with

$$e_{\cdot,IAE} := \int_{t_1}^{t_2} |e(t)| \mathrm{d}t \approx \sum_{i=I_1}^{I_2} |e(iT_s)| \tag{13}$$

where T_s stands for the sampling period and $t_\cdot = T_s I_\cdot$. Denote u_{IAE} as the overall manipulated input energy formulated in terms of (13) where $u(t)$ is substituted for $e(t)$. Let the overall error (for $t_1 = 0, t_2 \to \infty$) be e_{IAE}.

Following sensitivities (6), we clearly have $N_k = 3$, $N_f = 8$ and choose $\Delta m_0 = \Delta m_1 = 0.001$, $\Delta\lambda = 0.1$. The eventual results received by simulations are summarized in Table I.

TABLE I. COMPUTED VALUES OF $\Sigma_j(\overline{k}_i)$

f_j \ k_i	m_0	m_1	λ
$\delta e_{lc,\max}$	$-1.68 \cdot 10^{-2}$	$-4.55 \cdot 10^{-4}$	$-1.27 \cdot 10^{-2}$
$\delta e_{cc,\max}$	$9.74 \cdot 10^{-2}$	0.27	0.72
$\delta e_{d,\max}$	$-4.82 \cdot 10^{-2}$	$1.95 \cdot 10^{-2}$	$5.19 \cdot 10^{-2}$
$e_{lc,IAE}$	-0.32	-0.11	-0.43
$e_{cc,IAE}$	-0.18	$1.22 \cdot 10^{-2}$	$-9.47 \cdot 10^{-2}$
$e_{d,IAE}$	-0.26	$-1.01 \cdot 10^{-2}$	$-3.01 \cdot 10^{-2}$
e_{IAE}	-0.22	$-5.87 \cdot 10^{-2}$	-0.26
u_{IAE}	$1.01 \cdot 10^{-2}$	$4.14 \cdot 10^{-4}$	$3.31 \cdot 10^{-3}$

Note that in the numerical experiment, $r(t)$ was set as a linearly ascending signal for $t \in [0,3000]$ s, then as a constant value for $t \in (3000,9000]$ s and, after a step-down change, as a constant again for $t > 9000$ s. The step-down load disturbance enters at $t = 6000$ s. It was set $t_1 = 3000, t_2 = 6000$ for $\delta e_{lc,\max}$ and $e_{lc,IAE}$, $t_1 = 9000, t_2 = 11000$ for $\delta e_{cc,\max}$ and $e_{cc,IAE}$, and $t_1 = 6000$, $t_2 = 9000$ for $\delta e_{d,\max}$ and $e_{d,IAE}$.

When controlling temperature, the user usually requires not to be faced with a momentary deviation from the reference value, and from the economical point of view, it is desirable to have the overall consumed energy as low as possible. Due to these reasons, weight coefficients in (7) can be set as $l = 1$ except for $\delta e_{\cdot,\max}$ and u_{IAE} with $l = 2$. The eventual parameter values then read $m_0 = 0.0455$, $m_1 = 0.0016$, $\gamma = 0.248$. One can verify that robust performance conditions (11) is satisfied for this setting, and hence it can be used for our control task. In Figs. 1 and 2, the manipulated input and controlled output temperature are, respectively, displayed. Both simulations and laboratory measurements are given to the reader in order to be mutually compared. The outputs, apparently, almost coincide; whereas the deviation in the inputs have been caused by different ambient temperatures during the identification phase and the control experiment. The complete comments and additional information can be found in [13].

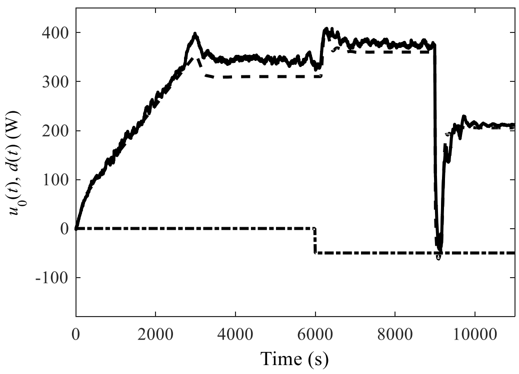

Fig. 1. Control inputs ($u_0(t)$) responses – measuread (solid) and simulated (dash) – and the load disturbance signal $d(t)$ (dash-dot).

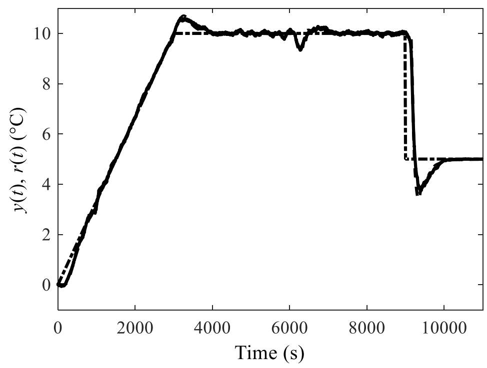

Fig. 2. Controlled outputs ($y(t)$) responses – measuread (solid) and simulated (dash) – and the reference value $r(t)$ (dash-dot).

V. Conclusions

This contribution has addresses a simple controller parameters determination setting idea that attempts to combine various control response measures so that a quasi-optimal compromise solution is obtained. The methodology has been demonstrated by a real-measurement study example when controlling a thermal process with state delays. Presented results have proved its very good applicability.

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References

[1] R.W. Serth and T.G. Lestina, Process Heat Transfer - Principles, Applications and Rules of Thumb, 2nd ed., New York: Academic Press, 2014.

[2] R.K. Shah and D.P. Sekulic, Fundamentals of Heat Exchanger Design, New Jersey: Wiley, 2003.

[3] J. Alvarez-Ramirez, I. Cervantes, and R. Femat, "Robust controllers for a heat exchanger," Ind. Eng. Chem. Res., vol. 36, no. 2, pp. 382-388, 1997.

[4] A. Vasičkaninová, M. Bakošová, A. Mészáros, and J.J. Klemeš, "Neural network predictive control of a heat exchanger," Appl. Therm. Eng., vol. 31, pp. 2094-2100, 2011.

[5] S. Wang, D.C. Gao, Y. Sun, and F. Xiao, "An online adaptive optimal control strategy for complex building chilled water systems involving intermediate heat exchangers," Appl. Therm. Eng., vol. 50, no. 1, pp. 614-628, 2013.

[6] P. Zítek and J. Hlava, "Anisochronic internal model control of time-delay systems," Control Eng. Pract., vol. 9, no. 5, pp. 501-516, 2001.

[7] L. Pekař, R. Prokop, and P. Dostálek, "Circuit heating plant model with internal delays," WSEAS Trans. Systems, vol. 8, no. 9, pp. 1093-1104, 2009.

[8] S. Talaš and V. Bobál, "Measurable error compensation with GPC in a heat-exchanger with a traffic delay," in: Nostradamus 2014: Prediction, Modeling and Analysis of Complex Systems. Berlin: Springer, 2014, pp. 281-290.

[9] M. Bakošová and J. Oravec, "Robust model predictive control of heat exchangers," Chem Eng. Trans., vol. 73, pp. 1465-1470, 2012.

[10] J. Oravec, M. Bakošová, A. Mészáros, and N. Míková, „Experimental investigation of alternative robust model predictive control of a heat exchanger," Appl. Therm. Eng., vol. 105, pp. 774-782, 2016.

[11] J.Q. Huang and F.L. Lewis, "Neural-network predictive control for nonlinear dynamic systems with time-delay," IEEE Trans. Neural Networ., vol. 14, pp. 377-389, 2003.

[12] V. Bobál, P. Dostál, M. Kubalčík and S. Talaš, "LQ control of heat exchanger – design and simulation," in Proc. 29th Europ. Conf. Model. Simul. (ECMS 2015), Varna, Bulgaria, 2015, pp. 239-245,

[13] L. Pekař and R. Prokop, "Algebraic robust control of a closed circuit heating-cooling system with a heat exchanger and internal loop delays," Appl. Therm. Eng., vol. 113C, pp. 1464-1474, 2017.

[14] L. Pekař and R. Prokop, "The revision and extension of the RMS ring for time delay systems," Bull. Pol. Acad. Sci. Tech. Sci., vol. 65, 2017, accepted.

[15] C. Doyle, B.A. Francis, and A.R. Tannenbaum, Feedback Control Theory. New York: McMillan, 1992.

[16] P. Dostálek, J. Dolinay, and V. Vašek, "Design and implementation of portable data acquisition unit in process control and supervision applications," WSEAS Trans. Systems and Control, vol. 3, no. 9, pp. 779-788, 2008.

[17] L. Pekař, J. Korbel, and R. Prokop, "TFC robust control design for time delay systems - Analysis and example", in Proc. 2013 Int. Conf. Process Control (PC 2013), Štrbské Pleso, Slovakia, 2013, pp. 324-329.