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Robust Model Predictive Control of Heat Exchanger Network in the Presence of Fouling

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The aim of this paper is to present robust model predictive control (MPC) with integral action to optimize control performance of heat exchangers selected from a network, in the presence of fouling. The robust MPC represents an advanced optimization-based strategy to handle uncertain systems. The integral action is implemented to remove steady-state errors of controlled variables. The time-varying parameters of the heat exchangers in the presence of fouling are handled in the form of parametric uncertainties. Simulation of the closed-loop control confirms the significantly improved control performance.

1. Introduction

Energy supply and its efficient use are crucial to assure prosperous economies and achieve energy savings, see e.g. Liu et al. (2016). Nowadays, advanced strategies are implemented to operate heat exchanger networks efficiently (Yong et al., 2016). Control performance of heat exchanger operation is decreased by fouling understood as the deposition of foreign matter on the heat transfer surface. Modeling of fouling in heat exchangers remains a burden in industrial operations and represents a challenging field of research (Zahid et al., 2016). Mathematical formulation of the fouling in a heat exchanger is determined by the physical properties of the heat carrier and material of the unit, and hydraulic characteristics of the flow of heat-exchanging media (Demirskyy et al., 2016).

Energy savings and operational optimization attracted high interest of researchers in the past two decades (Klemeš and Varbanov, 2013). Model predictive control (MPC) represents state-of-art in model-based control. The receding horizon strategy enables optimizing of the control action in each step considering various requirements and constraints, see, e.g., Mayne (2014). As the heat exchangers have various uncertain parameters, robust MPC can optimize the control performance subject to uncertainties. Linear matrix inequalities (LMIs) serve to formulate a convex optimization problem in the form of semidefinite programming (SDP) that is solved efficiently in polynomial time.

Vasičkaninová et al. (2011) designed the neural network predictive control (NNPC) structure for the heat exchangers to ensure energy savings. Vasičkaninová and Bakošová (2015) investigated the control performance of the neural network predictive control combined with an auxiliary fuzzy controller designed for the heat exchanger network. Bakošová and Oravec (2014) designed LMI-based robust MPC for the heat exchanger network. Simulation of the closed-loop control performance confirmed the possibility to assure energy savings. Oravec et al. (2016a) studied various alternative robust MPC strategies for the heat exchangers. Oravec et al. (2016b) investigated experimental analysis of the alternative robust MPC design for a laboratory heat exchanger. Klaučo and Kvasnica (2017) proposed the MPC-based scheme of the reference governor to improve safety and economic performance of a boiler-turbine system controlled by a set of interconnected PI controllers.

In this work, an industrial benchmark system is considered. The controlled system represents selected heat exchanger units from a network coupled with a Crude Distillation Unit (CDU). The mathematical model was built and validated based on the data recorded in three years of the plant operation. This paper directly extends the results of the works Trafczynski et al. (2016a) and Trafczynski et al. (2016b), where a detailed model of the heat exchanger unit was derived and PID controllers were designed to reduce the impact of fouling. Fouling leads to burning of extra fuel to compensate for reduced heat recovery and requires increased costs caused by cleaning interventions, etc. Therefore, an advanced optimization-based control strategy was implemented to overcome these drawbacks. The alternative robust MPC strategy (Oravec and Bakošová, 2015a) was implemented to optimize the control performance of the complex benchmark, i.e., the network of shell-and-tube heat exchangers in the presence of fouling. Simulations of the closed-loop control were performed in MATLAB/Simulink environment and they demonstrated the efficacy of the proposed strategy.

2. Controlled shell-and-tube heat exchangers

The controlled system was adopted from the paper Trafczynski et al. (2016a), i.e., selected heat exchanger units from a network coupled with a CDU rated 120 kg crude oil per second were considered. The heat exchanger network consisted of shell-and-tube heat exchangers (Figure 1). Each of the selected units was considered as an array of cells in which the heat exchange was modelled using the lumped-parameter approach. The developed model described the transient states of the heat exchangers based on the energy balance of a volume in which changes in the state of tube-side fluid, tube walls and shell-side fluid were accounted for. The heat exchangers were identified in the form of input-output models represented by the transfer functions. This approach had an advantage of yielding simple analytical relationships which were sufficiently accurate as far as the number of cells defined in the heat exchanger structure was large. The dynamic behaviour of the derived model was successfully verified based on the data records collected in three years of operation of the real heat exchanger network coupled with the CDU. Trafczynski et al. (2016a) presented the detailed model.

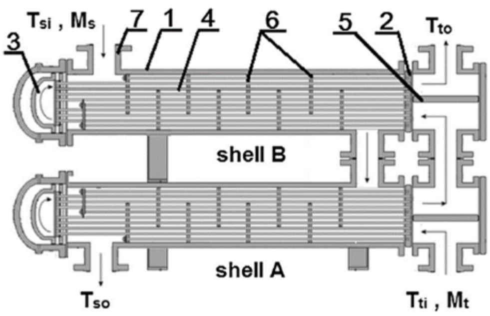

Figure 1: Flow arrangement in two series-connected heat exchangers, TEMA type AES with floating head: (1) shell, (2) tube sheet, (3) floating head, (4) tubes, (5) pass divider, (6) baffles, and (7) nozzle (Trafczynski et al., 2016a).

Fouling represented a serious problem in industrial operation. The fouling decreased the efficacy of the devices, lead to the energy loses, and increased the operational costs (Jelemenský et al., 2016). The fouling changed the plant parameters in time. Therefore, an advanced control strategy was needed to overcome these obstacles.

3. Alternative robust model predictive control with integral action

To meet the goals of the control task, we used the alternative robust MPC strategy, see e.g. Oravec et al. (2015), Oravec and Bakošová (2015a). To the robust MPC design, the linear time-invariant state-space model in the discrete-time domain derived using the sampling period t_s = 5 s is described by

$$
\begin{aligned}
&x(k+1) = Ax(k) + Bu(k),\ x(0) = x_0,\\
&y(k) = Cx(k),\\
&[A, B] \in \Omega,\ \Omega = \mathrm{convhull}\left(\left[A^{(v)}, B^{(v)}\right], \forall v \in \{1, \dots, n_v\}\right),
\end{aligned}
\tag{1}
$$

where k represents the discrete time, $x(k)$ is the vector of states, $u(k)$ is the vector of control inputs, $y(k)$ is the vector of the system outputs. The matrices $A^{(v)}$, $B^{(v)}$, C have appropriate dimensions. The model in Eq(1) is an uncertain system with polytopic uncertainty. For the uncertain model of the system, one can obtain four vertices that correspond to (i) the clean heat exchanger at the beginning of operation; (ii) the heat exchanger with fouling after one year of operation time; (iii) the heat exchanger with fouling after two years of operation time; and (iv) the heat exchanger with fouling after three years of operation time. The increasing operation time corresponds to increasing effect of fouling. The matrices $A^{(v)}$, $B^{(v)}$, $v = 1,\ldots,4$, describe the vertex systems of the uncertain system in Eq(1).

Moreover, the system in Eq(1) was extended to implement the robust MPC with integral action that ensures the offset-free control.

Then the robust static state-feedback control problem in the discrete-time domain can be formulated as follows: find a state-feedback control law (Oravec et al., 2015)

$$u(k) = F_k x(k), \tag{2}$$

for the system described by Eq(1). The matrix F_k in Eq(2) represents the static state-feedback robust controller for the k-th control step.

Quality of the control performance is expressed by the quadratic cost function

$$J = \sum_{k=0}^{n_k} \left(J_x(k) + J_u(k) \right) = \sum_{k=0}^{n_k} \left(x(k)^T W_x x(k) + u(k)^T W_u u(k) \right), \tag{3}$$

where n_k is the total number of control steps. For design purposes the infinite control horizon is assumed, and W_x, W_u are real square symmetric positive-definite weight matrices of the system states $x(k)$ and the system inputs $u(k)$, respectively. The aim is to design the controller F_k that ensures robust stability of all considered vertex systems and minimizes the quadratic criterion J in Eq(3). The control performance can be improved by taking into account symmetric constraints on the system outputs $y(k)$ and inputs $u(k)$ in the form

$$\|y(t)\|^2 \leq y_{\max}^2, \|u(t)\|^2 \leq u_{\max}^2, \tag{4}$$

Following conditions hold for the symmetric positively defined Lyapunov matrix P_k and the feedback controller F_k

$$P_k = \gamma_k X_k^{-1}, Y_k = F_k X_k, \Rightarrow F_k = Y_k X_k^{-1}, \tag{5}$$

where γ_k is the auxiliary optimization parameter, X_k is the symmetric positively defined matrix, and Y_k represents the auxiliary matrix enabling the evaluation of the robust feedback controller F_k. The robust stabilization problem can be solved as the robust MPC convex optimization problem based on the LMIs as follows:

$$\min_{\lambda_k, X_k, Y_k} \gamma_k \tag{6}$$

subject to

$$\begin{bmatrix} 1 & x_k^{\mathrm{T}} \\ * & X_k \end{bmatrix} \geq 0, \tag{7}$$

$$\begin{bmatrix} X_k & \left(A^{(v)} X_k + B^{(v)} \left(E_j Y_k + E_j^{-} U_k \right) \right)^{\mathrm{T}} \\ * & X_k \end{bmatrix} > 0, \tag{8}$$

$$\begin{bmatrix} X_k & \left(A^{(0)} X_k + B^{(0)} \left(E_j Y_k + E_j^{-} U_k \right) \right)^{\mathrm{T}} & X_k \sqrt{W_x} & \left(E_j Y_k + E_j^{-} U_k \right)^{\mathrm{T}} \sqrt{W_u} \\ * & X_k & 0 & 0 \\ * & * & \gamma_k I & 0 \\ * & * & * & \gamma_k I \end{bmatrix} \geq 0 \tag{9}$$

where $v = 1,\ldots, n_v$. The symbol * denotes a symmetric structure of the matrix, and I, 0 are the identity and zero matrices of appropriate dimensions, respectively. X_k is the symmetric positively defined matrix. The symmetric constraints on the control inputs and the controlled outputs in the form of Eq(4) can be added to the optimization problem Eq(6) – Eq(7) in the following LMI form

$$\begin{bmatrix} u_{\max}^2 I & U_k \\ * & X_k \end{bmatrix} \geq 0, \begin{bmatrix} X_k & \left(A^{(v)} X_k + B^{(v)}\left(E_j Y_k + E_j^- U_k\right)\right)^\mathrm{T} C^\mathrm{T} \\ * & y_{\max}^2 I \end{bmatrix} \geq 0 \tag{10}$$

where $v = 1,\ldots, n_v$, $j = 1,\ldots, n_u$. The matrices E_j are the diagonal matrices with all variations of 1 and 0 on the principal diagonal and zeroes elsewhere; E_j^- are the complement matrices obtained as $E_j^- = I - E_j$. The idea of this extension is to take into account all variations of the constrained and unconstrained control inputs. Then the algorithm for the $RMPC_3$ can be formulated in following eight steps:

Step 1: Set parameter $k = 0$.
Step 2: Set number of control steps N, initial conditions of states $x(0)$, values of the symmetric constraints on control input $u_{\max}$ and output $y_{\max}$.
Step 3: Set parameter $k = k + 1$.
Step 4: Set the values of states $x(k)$.
Step 5: Solve optimization problem described by Eq(6), Eq(7), Eq(10), Eq(11), Eq(12) to evaluate X_k, Y_k.
Step 6: Design the matrix F_k of the feedback controller using Eq(5).
Step 7: Calculate the control input $u(k)$ using the control law Eq(2).
Step 8: If the parameter $k < N$ then go to the *Step 3* else *Stop*.

4. Results and discussion

This work extends the results of the PID heat exchangers control presented in the work of Trafczynski et al. (2016a). An analogous control setup was considered, see Figure 2. The controlled variables were the tube-side outlet temperatures T_{t0}. The manipulated variables were shell-side stream flow rates M_s. The other process variables were the disturbances, i.e., the tube-side and the shell-side inlet temperatures T_{ti}, T_{si}, and the tube-side mass flow rates M_t.
Instead of PID controllers, we implemented the robust MPC to handle the time-varying behaviour of the system using parametric uncertainties. The robust MPC with integral action was designed to ensure offset-free reference tracking. The controlled system consisted of four heat exchanger units denoted E11AB, E15AB, E30AB, and E35AB, see Trafczynski et al. (2016a). The simulations of the closed-loop control were done using the linear models of the heat exchangers in the form of Eq(1). The matrices A, B, C of four heat exchanger units denoted by E11AB, E15AB, E30AB, E35AB are given in Table 1. All the units comprise two exchangers (A and B) connected in series.

Table 1: Heat exchanger units E11AB, E15AB, E30AB, E35AB - matrices A, B, C of the model in Eq(1).

Operation time [years]	Matrix	E11AB	E15AB	E30AB	E35AB
0	A	0.9248	0.9498	0.9460	0.9083
	B	0.1250	0.1250	0.1250	0.2500
	C	0.1804	0.0924	0.0865	0.1760
1	A	0.8991	0.9281	0.9311	0.8926
	B	0.1250	0.1250	0.1250	0.2500
	C	0.1453	0.0978	0.0082	0.2148
2	A	0.9237	0.9270	0.9200	0.9260
	B	0.2500	0.2500	0.2500	0.2500
	C	0.1556	0.1459	0.1535	0.1658
3	A	0.9116	0.9160	0.8991	0.9131
	B	0.1250	0.1250	0.1250	0.1250
	C	0.1839	0.1680	0.1776	0.2086

The weights of the quadratic criterion J in Eq(3) were assumed as $W_x = 2$, $W_u = 1$. Integral action was designed with the same weighting matrix as W_x. The closed-loop control was simulated by MATLAB/Simulink R2014b using CPU i5 1.7 GHz and 6 GB RAM. The robust MPC was designed using MUP toolbox (Oravec and Bakošová, 2015b), optimization problem was formulated by the YALMIP toolbox (Löfberg, 2004) and solved by the solver MOSEK. The obtained results of robust MPC of the tube-side outlet temperatures are depicted in Figures 3, 4. The temperature is presented in the normalized form, i.e., the robust MPC investigated the unit step-change of the set-point. Figures 3 and 4 show the control trajectories during three years of fouling build-up for the units E11AB (Figure 3a)), E15AB (Figure 3b)), E30AB (Figure 4a)), and E35AB (Figure 4b)). As can be seen, the robust MPC with integral action ensured the offset-free set-point tracking for all the heat exchangers. The original control trajectories generated by the considered PID controllers with adjustment of the parameters are shown in Trafczynski et al. (2016a). Compared to those results, the robust MPC significantly improved the control performance and reduced the overshoots of the temperature. Therefore, the optimized control performance may lead to significant energy savings.

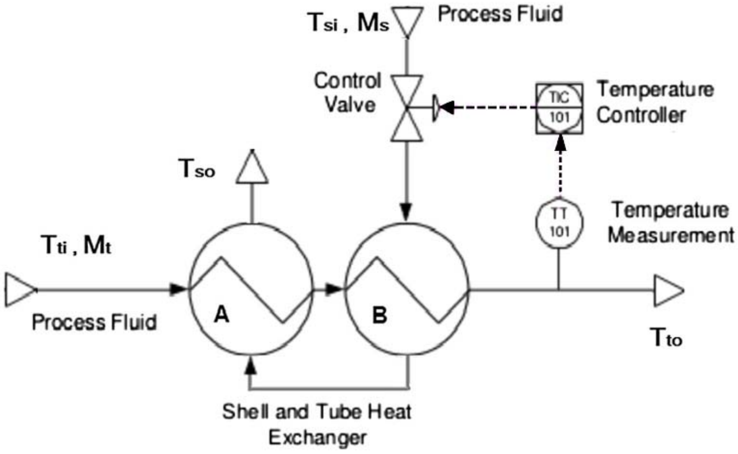

Figure 2: Scheme of a heat exchanger control (Trafczynski et al., 2016a).

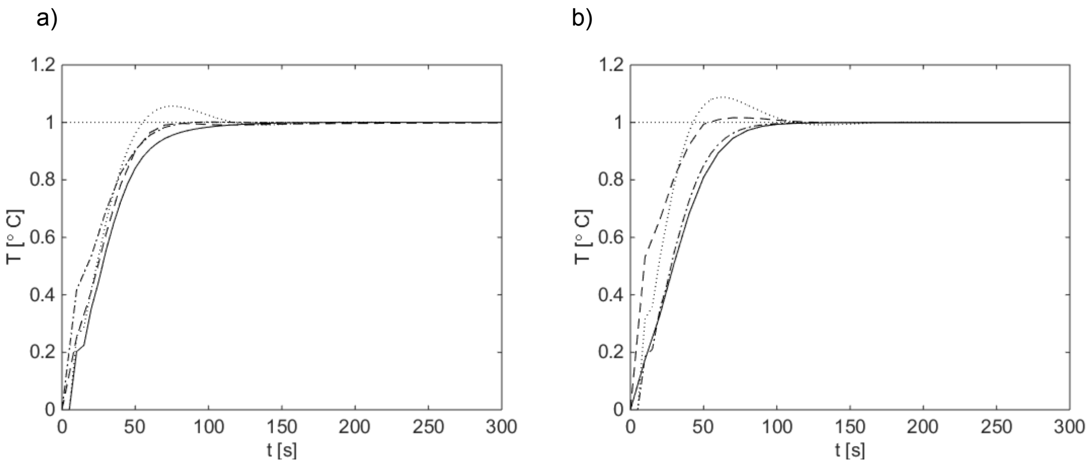

Figure 3: Control performance of E11AB (a) and E15AB (b), clean (solid), after 1year (dashed), after 2 years (dash-dotted), and after 3 years (dotted).

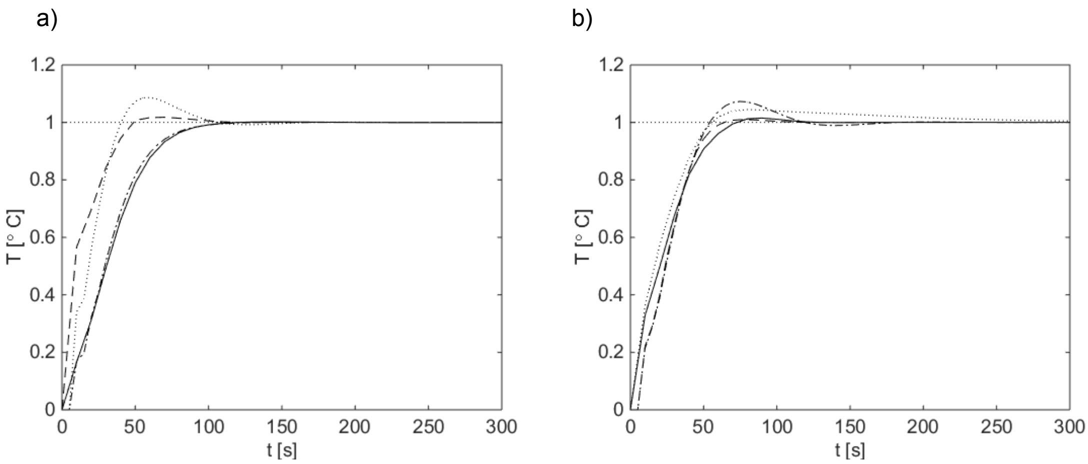

Figure 4: Control performance of E30AB (a) and E35AB (b), clean (solid), after 1 year (dashed), after 2 years (dash-dotted), and after 3 years (dotted).

5. Conclusions

The paper presents the robust MPC with integral action implemented to the control of the heat exchangers in the presence of fouling. The simulation results confirmed significant improvement of the control performance and a reduction in the oscillation behaviour, compared to the original PID control strategy. Further research will be focused on the implementation of the presented advanced strategy to the complex non-linear model of the entire heat-exchanger network.

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