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PREDICTIVE CONTROL OF ASYMMETRIC HEAT EXCHANGER

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Abstract

Heat exchange is a classical thermal process which occurs in a wide range of industrial technologies, particularly in the energetic and chemical industry. The paper is focused on a problem of production of liquid (water) with a given temperature course in time. Heating or cooling of inflow water is realized by a heat exchanger which is equipped with heating element and a spiral tube which can serve as a cooling element. The water inside the exchanger can serve as a tank for various chemical or technological operations. The need for tempered water is quite common in many industry branches. From the control point of view, the controlled system is asymmetrical; it has two inputs (cooling and heating) and one output – temperature of water inside the exchanger. A set of predictive controllers were designed to cope with the problem and these controllers were verified and compared by a real-time control of Multifunction Process Control Teaching System (MPCTS) – the Armfield PCT 40.

Key words

Predictive control, Recursive least squares method, TISO system, Heat exchanger, Real-time control

1 Introduction

Most of technological and chemical industrial processes are temperature dependant and a large part of them can be performed only within a given temperature range. Especially biochemical processes are highly nonlinear and optimum performance can be achieved only within quite narrow temperature limits. Moreover, the optimal conditions from the economical point of view where the process is the most effective are often close to the technological limits and these limits are often given by a temperature. Exceeding of the limits leads to a great decrease of efficiency and can also cause damage of equipments. Therefore maintenance of the temperature is one of crucial parts of many industrial processes. One of effective approaches of maintaining the process temperature is usage of water because of its high thermal capacitance. Many chemical processes also use a tempered liquid as one of the reactants.

A heat exchanger can serve as a source of a tempered liquid for various types of processes mentioned above. The temperature of a heat exchanger content can be generally controlled by heating or by cooling. The heating is usually implemented by a electrical heating element or a pipe with a heating liquid. Cooling can be accomplished by heat exchange with the surrounding environment or more effectively by heat exchange with a cooling element. A cold water pipe leading through the heat exchanger often serves as a cooling element.

From the control point of view, the heat exchanged can be considered an asymmetric control system with two inputs and one output. The inputs are control signals of the heating and cooling element and the output is the temperature of liquid inside the exchanger. One of suitable approaches of solving this problem is model predictive control.

The Model Predictive Control (MPC) is one of the control methods which have developed considerably over a few past years. Predictive control is essentially based on discrete or sampled models of processes. Computation of appropriate control algorithms is then realized mostly in the discrete domain.

The term Model Predictive Control designates a class of control methods e.g. [Maciejowski, 2002; Rossiter, 2003; Camacho and Bordons, 2004; Mikleš and Fikar, 2008].

Theoretical research in the area of predictive control has a great impact on the industrial world and there are many applications of predictive control in industry. Its development has been significantly influenced by industrial practice. At present, predictive control with a number of real industrial applications belongs among the most often implemented modern industrial process control approaches. A fairly actual and extensive surveys of industrial applications of predictive control are presented in [Morari and Lee, 1999; Quin and Bandquel 1996; Quin and Bandquel, 2000; Quin and Bandquel, 2003].

One of the major advantages of predictive control is its ability to do on-line constraints handling in a systematic way. Almost all industrial applications hold constraints of input, output and state space variables. The predictive control strategy therefore eliminates drawbacks of the other optimal methods like Linear Quadratic (LQ) and Linear Quadratic Gaussian (LQG) methods which operate on a finite horizon without capability to handle constraints. In practical control problems, actuators are obviously limited in their operational ranges. This is also the case of the laboratory heat exchanger realized on the Multifunction Process Control Teaching System – the Armfield PCT 40.

2 Multifunction Process Control Teaching System

2.1 Description of the MPCTS

The through-flow heat exchanger is a part of the MPCTS – the Armfield PCT40. This device is designed especially for teaching of a wide range of technological and chemical processes, such as temperature control in heat exchangers, flow control, level control in water tanks, pressure control and finally conductivity and pH control in additional PCT41 and 42 units, which is continuous-stirred tank reactor. The schematic representation of the multifunctional model is shown in Figure 1.

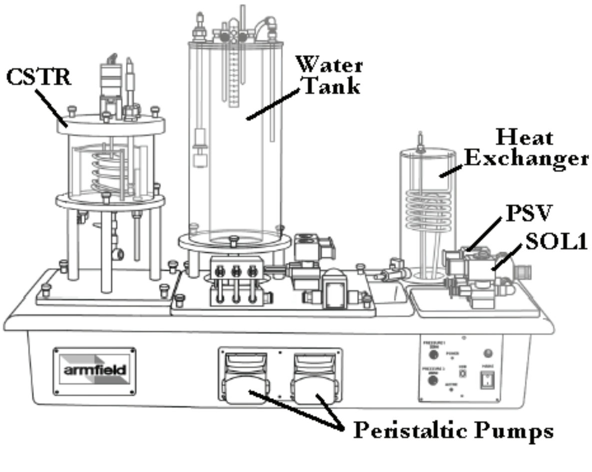

Figure 1. Schematic representation of multifunctional process control teaching system PCT40

The PCT40 contains everything that is needed to perform a range of closed-loop process control experiments in conjunction with a personal computer. It includes a variable volume process tank, a hot water tank with electric heater and indirect heating/cooling coil, a hot water pump, two non-dedicated pumps, three on/off solenoid valves (SOL1 – SOL3) and proportioning valve (PSV). The instrumentation includes temperature sensors, two differential water pressure sensors, a mechanical level sensor (float switch) and an electronic level sensor (conductivity). The inlets and outlets of the various pumps, valves and tanks are brought to a connection manifold, which uses self-sealing quick release fittings. This allows the configuration to be quickly changed, offering a wide variety of different loops.

The PCT40 includes a computer interface (USB), and all of the parameters can be controlled directly from the computer, i.e. the pump speeds, the valve positions and the heater power. The computer also displays the readings from the various measurement sensors.

2.2 Description of the Through-flow Heat Exchanger

Although the unit PCT40 is mainly intended to real – time verification of SISO controllers, in our case it was used for control of a system with two inputs and single output (TISO).

The inputs are the heater power, handled by Solid State Relay (SSR), and the water flow rate qc in the heating/cooling coil. The controlled variable is the temperature T measured by the sensor T, which is placed inside the tank. A constant amount of inlet and outlet water, which ensures a constant water level in the tank, is realized by equal adjustment of flow rate q by means of two peristaltic pumps A and B. A principle scheme of the laboratory equipment is in Figure 2.

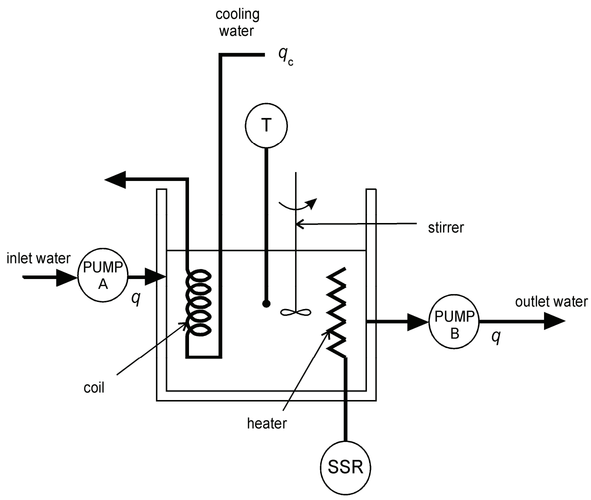

Figure 2. Schematic diagram of the laboratory apparatus

2.3 Analytical model of the through-flow heat process

The dynamics of the through-flow heat process is described by one ordinary differential equation and two partial differential equations. Heat balance in the stirred area is described by the following equation:

$$\frac{dT}{dt} = \frac{q}{V}\left(T_{in} - T\right) + \frac{Q - Q_c}{V\rho c_p} \tag{1}$$

with an initial condition $T\left(0\right) = T^s$, where

$$Q_c = \pi d_2 \alpha_2 \left(LT - \int_0^L T_p dz \right) \tag{2}$$

The heat balance equation of the coolant pipe has the form

$$\frac{\partial T_p}{\partial t} = \frac{4}{\left(d_2^2 - d_1^2\right)\rho_p c_{pp}} \left[d_2 \alpha_2 \left(T - T_p\right) - d_1 \alpha_2 \left(T_p - T_c\right) \right] \quad (3)$$

with an initial condition $T_p(z,0) = T_p^s(z)$.

The last heat balance equation of the coolant is

$$\frac{\partial T_c}{\partial t} + \frac{4q_c}{\pi d_1^2} \frac{\partial T_c}{\partial z} = \frac{4\alpha_1}{d_1 \rho_c c_{pc}} \left(T_p - T_c\right) \quad (4)$$

with an initial condition $T_c(z,0) = T_c^s(z)$ and a boundary condition $T_c(0,t) = T_{cin}(t)$.

Denotation and physical units of particular variables are as follows:

$Q\left(\text{kJ min}^{-1}\right)$	heat supplied by heating,
$Q_c\left(\text{kJ min}^{-1}\right)$	heat taken by cooling,
$T(\text{K})$	water temperature in the area of exchanger,
$T_{in}(\text{K})$	temperature of inlet water,
$V\left(\text{m}^3\right)$	water volume in the exchanger,
$q\left(\text{m}^3\ \text{min}^{-1}\right)$	flow rate in the exchanger,
$q_c\left(\text{m}^3\ \text{min}^{-1}\right)$	flow rate of the coolant,
$\rho, \rho_p, \rho_c\left(\text{kg m}^{-3}\right)$	densities (water in the exchanger, coolant pipe, coolant),
$T_p(\text{K})$	temperature of the coolant pipe,
$T_c(\text{K})$	temperature of the coolant,
$T_{cin}(\text{K})$	temperature of the coolant on the input,
$d_1, d_2(\text{m})$	inner and outer diameters of the coolant pipe,
$\alpha_1, \alpha_2\left(\text{kJ m}^{-2}\ \text{min}^{-1}\ \text{K}^{-1}\right)$	heat transfer coefficients,
$c_p, c_{pp}, c_{pc}\left(\text{kJ kg}^{-1}\ \text{K}^{-1}\right)$	specific heat capacities (water in the exchanger, coolant pipe, coolant),
$L(\text{m})$	length of the coolant pipe,
$t(\text{min})$	time,
$z \in \langle 0, L \rangle$	axial space variable.

Equations (1) – (4) represent general description of the through-flow heat process. In case of the through-flow heater which is realized on the MPCTS – the Armfield PCT40 the coolant is water. Therefore $\rho = \rho_c$ and $c_p = c_{pc}$.

2.4 Static characteristics of the model

The static characteristics of the PSV valve and the heat exchanger were measured experimentally.

The PSV valve contains a hysteresis which can be observed from its static characteristic in Figure. 3. A current flow rate through the PSV depends also on the water pressure on the input to the PCT40 system, but the shape and hysteresis of the PSV static characteristic remain the same. From Figure 3, it is obvious that for example value u_{PSV} equal to 1 V can result in any water flow rate in the range 866 ml min^{-1}–1543 ml min^{-1}. Due to this nonlinearity, a digital PI controller was used to handle the flow rate.

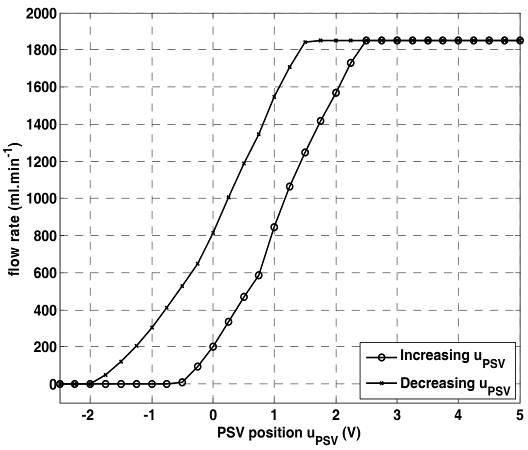

Figure 3. Static characteristic of PSV valve

The static characteristic of the heat exchanger is depicted in Figure 4.

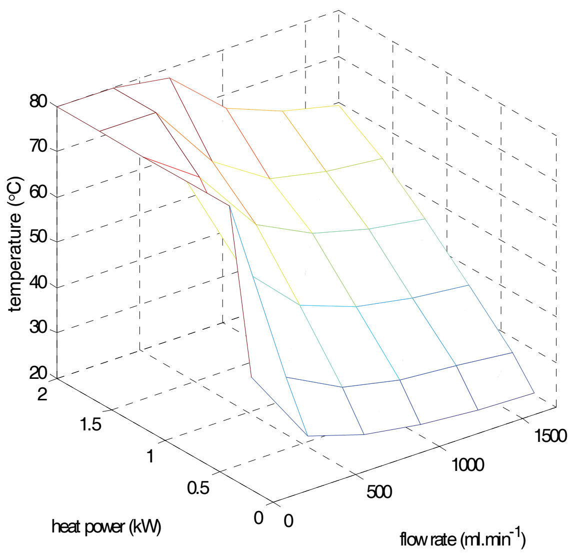

Figure 4. Static characteristic of heat exchanger

The static characteristic was measured for flow of cooling water up to 15700 ml min^{-1} and for the entire range of heating from 0 W to 2 kW. It should be mentioned that the temperature inside the exchanger is limited to approximately 80 °C. If the temperature exceeds this limit, the heating is switched off automatically.

Figure 4 proves that a relation of the temperature to the heater power is close to a linear function but a relation to the flow rate of cooling water is strongly nonlinear.

3 Design of the Controller

3.1 Model of the Exchanger

For the control purposes, the PCT40 heat exchanger was modelled as a Two Inputs Single Output (TISO) system. The inputs were flow of cooling water and input of the heater. The model obtained by a mathematical physical analysis of the heat exchanger (see chapter 2.3) can be simplified to second order discrete system in the form

$$A\left(z^{-1}\right)Y\left(z^{-1}\right)=B_1\left(z^{-1}\right)U_1\left(z^{-1}\right)+B_2\left(z^{-1}\right)U_2\left(z^{-1}\right)+E\left(z^{-1}\right) \quad (5)$$

$$\begin{aligned} y(k)+a_1y(k-1)+a_2y(k-2)= \\ =b_1u_1(k-1)+b_2u_1(k-2)+ \\ +b_3u_2(k-1)+b_4u_2(k-2)+e(k) \end{aligned} \quad (6)$$

where $E_s\left(z^{-1}\right)$ is a non-measurable random disturbance that is assumed to have zero mean value and constant covariance.

An on-line identification block has been incorporated into the model predictive controller to cope with nonlinearities of the controlled system [Kulhavý, 1987]

3.2 MPC criterion

The basic idea of MPC is to use a model of a controlled process to predict N future outputs of the process. A trajectory of future manipulated variables is given by solving an optimization problem incorporating a suitable cost function and constraints. Only the first element of the obtained control sequence is applied. The whole procedure is repeated in following sampling period. This principle is known as the receding horizon strategy. The computation of a control law of MPC is based on minimization of a given criterion. A quadratic criterion is used very often:

$$\begin{aligned} J_Q(k)=\sum_{j=1}^{N}\mathbf{e}(k+j)^2+\lambda_{Q1}\sum_{j=1}^{N_u}\Delta\mathbf{u}_1(k+j)^2+ \\ +\lambda_{Q2}\sum_{j=1}^{N_u}\Delta\mathbf{u}_2(k+j)^2 \end{aligned} \quad (7)$$

where $\mathbf{e}(k+j)$ is a vector of predicted control errors, $\Delta\mathbf{u}_1(k+j)$ and $\Delta\mathbf{u}_2(k+j)$ are vectors of future control increments, N is length of the prediction horizon, N_u is length of the control horizon and λ_{Q1}, λ_{Q2} are a weighting factor of control increments.

Not only the quadratic criterion was used, but also a MPC based on linear criterion was tested the form of the linear criterion was as follows:

$$\begin{aligned} J_L(k)=\sum_{j=1}^{N}\left|\mathbf{e}(k+j)\right|+ \\ +\lambda_{L1}\sum_{j=1}^{N_u}\left|\Delta\mathbf{u}_1(k+j)\right|+\lambda_{L2}\sum_{j=1}^{N_u}\left|\Delta\mathbf{u}_2(k+j)\right|+ \\ +\lambda_{L3}\sum_{j=1}^{N_u}\left|\mathbf{u}_1(k+j)\right|+\lambda_{L4}\sum_{j=1}^{N_u}\left|\mathbf{u}_2(k+j)\right| \end{aligned} \quad (8)$$

4 Experimental Examples

The model was connected with a PC equipped with a control and measurement PC card. MATLAB and Real Time Toolbox were used to control the system. A block scheme of the realized control loop is in Figure 5.

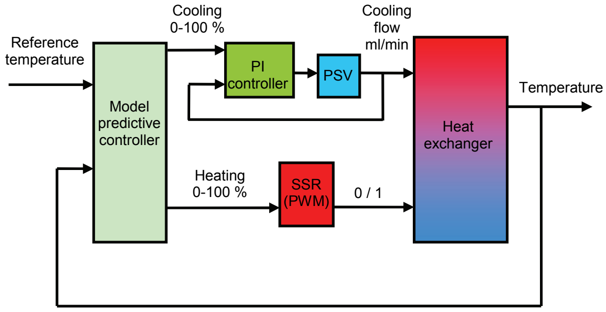

Figure 5. Block scheme of the control loop

The fist manipulated variable u_1 (flow rate) was handled by the valve (the block PSV in Figure 5). Due to nonlinear static characteristic of the valve (see Figure 3), setting of the valve position was implemented by a simple digital PI controller (the block PI in Figure 5) to ensure required cooling flow. An output enabling only *on* and *off* positions was available for the manipulated variable u_2 (heater power) because the heater is drive by a solid state relay (SSR). The control signal was then realized by pulse width modulation (the block PWM in Figure 5).

The model predictive controllers used to cope with described control problem were selected from the STuMPCoL – a Simulink library of self-tuning model predictive controllers [Chalupa, 2009]. This library has been designed in the MATLAB / Simulink environment to provide framework for testing of different model predictive controllers.

A principal detailed scheme of the realized control loop is presented in Figure 6. This control loop is common for all control experiments which were performed. The difference between individual experiments consists in usage of different model predictive controllers and different controller settings.

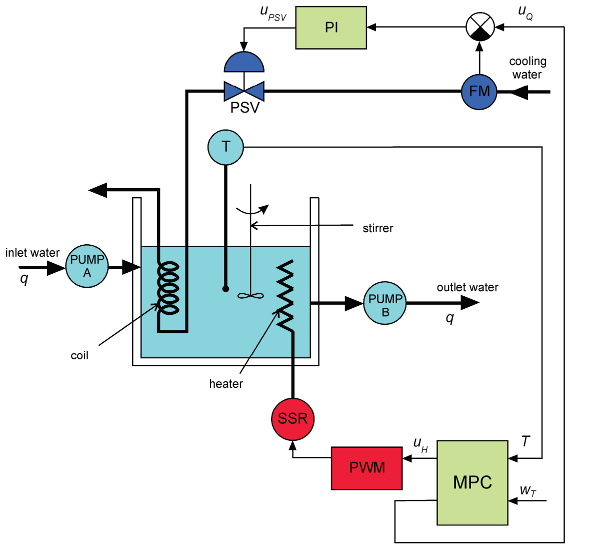

Figure 6. Detailed scheme of the control loop

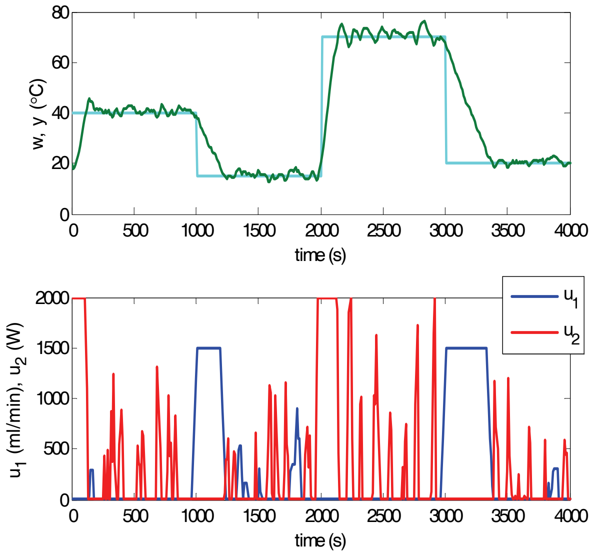

Figure 8. Predictive control of heat exchanger using linear criterion

Courses of the reference signal contain step changes in both directions. This is one of the most unfavourable situations which can occur in a closed loop control system. Within the steps also changes the operational range. This is one of the reasons for application of self-tuning controllers. An example of control course obtained by applying quadratic criterion is presented in Figure. 7.

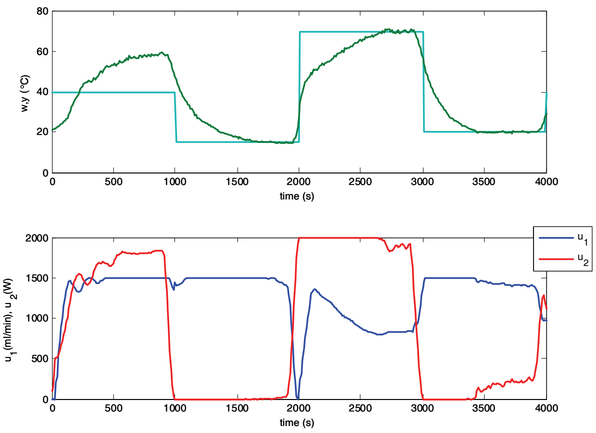

Figure 7. Predictive control of heat exchanger using quadratic criterion

In this case the control error (e) and differences of both control signals (Δu_1, Δu_2) were penalized as stated by equation (7). Direct penalization of control signals (u_1, u_2) was not used because it would have lead to nonzero steady state error.

It can be seen that control courses obtained by this pure quadratic criterion in the MPC are not optimal from the economical point of view. Cooling and heating is applied at the same time even in the steady states.

An example of control courses obtained by using linear criterion is presented in Figure 8.

In this case the control error (e) and differences of first control signals (Δu_1) and values of both control signals (u_1, u_2) were penalized as stated by equation (8). Penalization of differences of heating (u_2) was omitted because it does not have any practical consequence. The heating is realized using PWM and thus output of the solid state relay is switched on and off during each control period regardless of value of heating – except case of no heating (0%) and full heating (100%).

Obtained control courses have direct economical consequence. Proper setting of weights λ in the criterion (8) leads to the situation where zero steady state error is reached and control is economically optimal – i.e. both cooling and heating are not used un steady states.

The last presented control courses are shown in Figure 9.

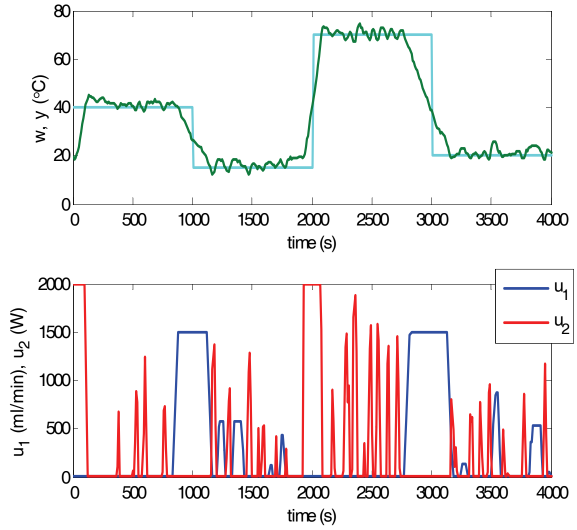

Figure 9. Predictive control of heat exchanger using modified linear criterion

These courses were obtained by the same settings as courses in the Figure 8, but the control and prediction horizons (N, N_u) were enlarged. The computation demands have increased but controller is able to react to changes of reference signal earlier compared to situation presented in Figure 8.

7 Conclusions

The paper was focused on the problem of nonlinear heat exchanger control. The model predictive control approach was successfully applied to this control problem. Various MPCs were designed and verified.

The main advantage of using the quadratic criterion in the MPC consists in smooth control courses. On the other hand, pure quadratic criterion cannot fulfil both zero steady state control error and economically optimal control.

The crucial advantage of applying linear criterion consists in economically optimal control even in case of using pure criterion without any further modifications. However, usage of the linear criterion leads to higher sensitivity to noise.

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