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AUTOMATIC CONTROL OF THE CONTAMINATED SOIL TREATMENT TECHNOLOGICAL PROCESS

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Abstract. The extension of a recently developed method for gain scheduling of linear controllers is applied for self-tuning of feed-forward/feed-back control system that is applied for automatic control of contaminated soil washing technological process. Adaptation of the feed-back and the feed-forward controller parameters to the time-varying state of controlled process refers to the process state model based transfer functions, which are up-dated on-line with the measured values of the state and disturbance variables.

Keywords: mathematical modeling, adaptation, automatic control, contaminated soil, clean-up.

1. Indroduction

An automatic control system investigated in this paper is related to the development of complex technology of cleaning soil contaminated with oil pollutants [1]. Realization of the soil washing technological process requires continuous regeneration of washing liquid circulating in the closed loop technological system, and accurate control of technological parameters. The controlled technological process is nonlinear and non-stationary and the process state at operating point changes in a wide range. Therefore, traditional linear controllers are not adequate to accurately control the process at a desired point. To improve performance of control systems, adaptation of controller parameters to the changing dynamics of the process is required.

Currently, self-tuning of commercial controllers is based on the artificial disturbances (step set-point or frequency responses) of the control system [2], or the controller gain scheduling, which refers to a particular process parameter that matches to the process state [3]. However, artificial disturbances are not acceptable during the soil washing process. The gain scheduling based on a single process parameter is not adequate for controlling the soil washing processes as the process state cannot be related to a single variable.

The aim of this work is to develop a self-tuning control system that accurately keeps up a required technological regime under process disturbances and set-point changes. In the control system, we apply a modified gain scheduling approach [4] for self-tuning of controller and disturbance compensator parameters, which does not require active disturbances of the controlled process and is based on the process state model based transfer functions and on-line measurements or estimates of the state variables.

2. Technological process

The technological scheme of the contaminated soil washing process is depicted in Figure 1.

The biosurfactant solution of proper concentration, temperature and pH is prepared in the tank 2. The prepared solution is pumped into the contaminated soil-washing site 3 through the fenestrate pipeline using high-pressure pump 6. The used biosurfactant solution containing the washed out oil pollutants is collected in the mechanical treatment well 4, in which the pollutants are mechanically separated from the washing liquid. After separation, the used washing liquid is collected in the well 5. The pump 7 returns the used liquid to the tank 2, in which continuous regeneration of the washing liquid is carried out.

The soil washing process is controlled via stabilization at desired levels of the technological parameters: temperature, pH and emulsification activity of the washing solution. The temperature is controlled by manipulating the flow-rate of heating water in a jacket of the tank 2. Emulsification activity of the regenerated solution is controlled by manipulating the inflow-rate of the concentrated biosurfactant from the vessel 1. pH is controlled by manipulating the flow-rate of sodium alkali solution. The pH control problem is similar to the biosurfactant concentration control.problem and is not investigated in this work.

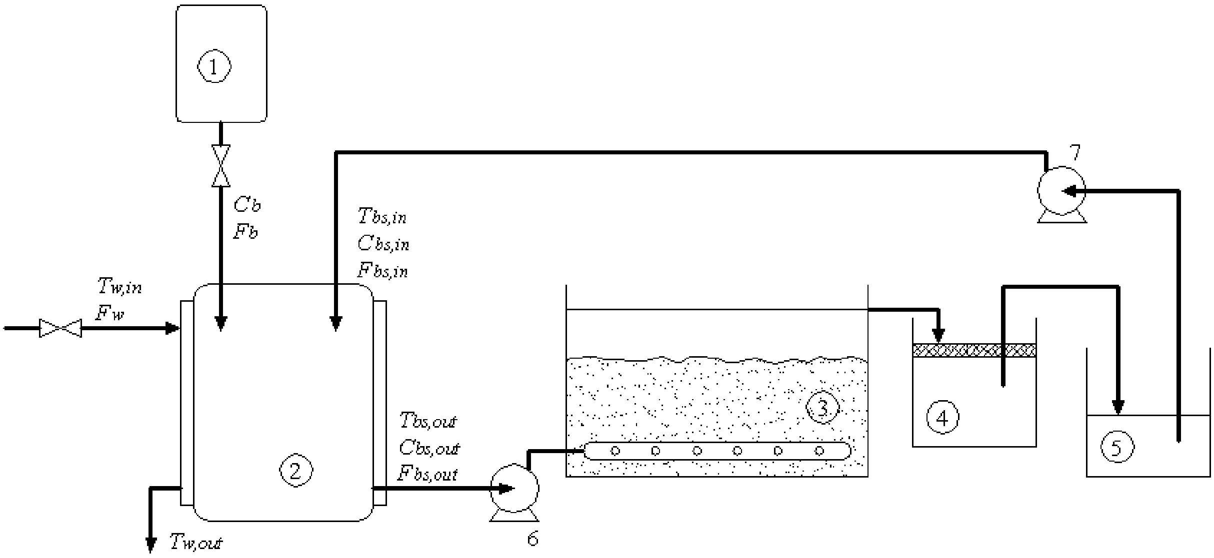

Figure 1. Technological scheme of washing soil contaminated with oil pollutants.1 - vessel with biosurfactant; 2 – tank for preparation of biosurfactant solution; 3 – contaminated soil washing site; 4 – mechanical treatment well; 5 – well for recycled biosurfactant solution; 6,7 – pumps for carrying out the circulation of biosurfactant solution

The process disturbances that task stabilization of the above technological parameters are changes of biosurfactant concentration in vessel 1 and the recycled washing solution, temperature of heating water and circulation rate of washing solution.

3. Mathematical model of the washing solution preparation process

Adaptation of controller parameters to the changing state of controlled process is based on the process state model.

Development of the process state model

The state variables are the controlled technological parameters: temperature and concentration of biosurfactant in washing solution, and temperature of the outlet heating water. The state equations are developed using energy and mass-balance conditions in the washing solution preparation tank and the jacket of heating water.

Heat balance for washing solution:

$$\begin{aligned}\rho_{bs}c_{bs}V\frac{dT_{bs,out}}{dt} &= hS\left(T_{w,out}-T_{bs,out}\right)+\\ &\rho_{bs}c_{bs}F_{bs,in}T_{bs,in}-\rho_{bs}c_{bs}F_{bs,out}T_{bs,out}-Q_l\end{aligned}, \quad (1)$$

heat balance for heating water:

$$\begin{aligned}\rho_w c_w V_j\frac{dT_{w,out}}{dt} &= \rho_w c_w F_w\left(T_{w,in}-T_{w,out}\right)-\\ &hS\left(T_{w,out}-T_{bs,out}\right)\end{aligned}, \quad (2)$$

mass balance for biosurfactant:

$$\begin{aligned}V\frac{dC_{bs,out}}{dt} &= F_{bs,in}C_{bs,in}+\\ &F_bC_b-F_{bs,out}C_{bs,out}\end{aligned} \quad (3)$$

where ρ_w, ρ_{bs} are the densities of heating water and washing solution, respectively (in practical calculations $\rho_w \approx \rho_{bs}$), kg/m^3; c_w, c_{bs} are specific heats of water and washing solution, respectively (in practical calculations $c_w \approx c_{bs}$), J/kg/^{o}C; C_b is concentration of concentrated biosurfactant, relative units; $C_{bs,in}$, $C_{bs,out}$ are concentrations of biosurfactant in the inlet and outlet washing liquid, respectively, relative units; h is a heat transfer coefficient through the unit area of heat transfer surface, J/m^2/h/^{o}C; F_b is inlet flow rate of concentrated biosurfactant (control variable), m^3/h; $F_{bs,in}$, $F_{bs,out}$ are inlet and outlet flow rates of washing liquid, respectively (at steady state operating conditions $F_{bs,in} \approx F_{bs,out} = F_{bs}$), m^3/h; F_w is flow rate of heating water (control variable), m^3/h; S is an area of the heat transfer surface, m^2; $T_{bs,in}$, $T_{bs,out}$ are temperatures of inlet and outlet washing liquid, respectively, ^{o}C; $T_{w,in}$, $T_{w,out}$ are temperatures of inlet and outlet heating water, respectively, ^{o}C; V is the volume of washing liquid in the tank, m^3; V_j is the volume of heating water in the jacket, m^3; Q_l is a term evaluating heat loss, J/h.

The values of the state equation (1)-(3) parameters that are used in simulation experiments are given in Table 1.

Table 1. Parameters of the state equations (1)-(3)

Physical constants	Nominal values of technological parameters	Initial values of state and control variables
$\rho_{bs} = 1000$ kg/m^3 $\rho_w = 1000$ kg/m^3 $c_{bs} = 4180$ J/kg/^{o}C $c_w = 4180$ J/kg/^{o}C	$C_b = 1.0$ rel. units $C_{bs,in} = 0.009$ rel. units $F_{bs} =$ 5 m^3/h $T_{bs,in} = 20$ ^{o}C $T_{w,in} = 70$ ^{o}C $V = 1.0$ m^3 $V_j = 0.5$ m^3 $hS =$ 2.1·10^7 J/h/^{o}C	$C_{bs,out} = 0.015$ rel. units $T_{bs,out} = 30$ ^{o}C $T_{w,out} = 39.95$ ^{o}C $F_b =$ 0.03 m^3/h $F_w =$ 1.664 m^3/h

Development of the state-model based transfer functions

The temperature of outlet heating water is not controlled during the washing liquid heating process, thus, it can be considered as a measurable technological parameter in the transfer function models.

Transfer functions of the control and the disturbance channels are obtained by linearization of the model equations (1) – (3) around the process current state point and applying the Laplace transform to the linearized equations:

$$s\mathbf{I}\Delta\mathbf{x}(s)=\left.\frac{\partial\mathbf{f}}{\partial\mathbf{x}}\right|_{\substack{\mathbf{x}=\mathbf{x}(t_k)\\ \mathbf{u}=\mathbf{u}(t_k)\\ \mathbf{d}=\mathbf{d}(t_k)}}\Delta\mathbf{x}(s)+\left.\frac{\partial\mathbf{f}}{\partial\mathbf{u}}\right|_{\substack{\mathbf{x}=\mathbf{x}(t_k)\\ \mathbf{u}=\mathbf{u}(t_k)\\ \mathbf{d}=\mathbf{d}(t_k)}}\Delta\mathbf{u}(s)+\left.\frac{\partial\mathbf{f}}{\partial\mathbf{d}}\right|_{\substack{\mathbf{x}=\mathbf{x}(t_k)\\ \mathbf{u}=\mathbf{u}(t_k)\\ \mathbf{d}=\mathbf{d}(t_k)}}\Delta\mathbf{d}(s), \tag{4}$$

where s denotes the Laplace variable; $\mathbf{x}$ is a vector of state variables, $\mathbf{x}=\left[T_{bs,out} \quad T_{w,out} \quad C_{bs,out}\right]^T$; $\mathbf{u}$ is a vector of control variables, $\mathbf{u}=\left[F_w \quad F_b\right]^T$; $\mathbf{d}$ is a vector of process disturbances, $\mathbf{d}=\left[F_{bs} \quad C_b \quad C_{bs,in} \quad T_{w,in} \quad T_{bs,in} \quad V\right]^T$; $\mathbf{f}$ is a vector of the state equation right-side functional relationships, $\Delta\mathbf{x}$, $\Delta\mathbf{u}$, $\Delta\mathbf{d}$ are small deviations of $\mathbf{x}$, $\mathbf{u}$, $\mathbf{d}$, respectively, from the process state point at time t_k ; and $\mathbf{I}$ is the identity matrix;

$$\frac{\partial\mathbf{f}}{\partial\mathbf{x}}=\begin{bmatrix}-\left(\dfrac{hS}{\rho_{bs}c_{bs}V}+\dfrac{F_{bs}}{V}\right) & \dfrac{hS}{\rho_{bs}c_{bs}V} & 0\\ \dfrac{hS}{\rho_w c_w V_j} & -\left(\dfrac{hS}{\rho_w c_w V_j}+\dfrac{F_w}{V_j}\right) & 0\\ 0 & 0 & -\dfrac{F_{bs}}{V}\end{bmatrix};$$

$$\frac{\partial\mathbf{f}}{\partial\mathbf{u}}=\begin{bmatrix}0 & 0\\ \dfrac{T_{w,in}-T_{w,out}}{V_j} & 0\\ 0 & \dfrac{C_b}{V}\end{bmatrix};$$

$$\frac{\partial\mathbf{f}}{\partial\mathbf{d}}=\begin{bmatrix}\dfrac{T_{bs,in}-T_{bs,out}}{V} & 0 & 0 & 0 & \dfrac{F_{bs}}{V} & -\dfrac{1}{V^2}\left[\dfrac{hS}{\rho_{bs}c_{bs}}\left(T_{w,out}-T_{bs,out}\right)+F_{bs}\left(T_{bs,in}-T_{bs,out}\right)-\dfrac{Q_L}{\rho_{bs}c_{bs}}\right]\\ 0 & 0 & 0 & \dfrac{F_w}{V_j} & 0 & 0\\ \dfrac{C_{bs,in}-C_{bs,out}}{V} & \dfrac{F_b}{V} & \dfrac{F_{bs}}{V} & 0 & 0 & -\dfrac{1}{V^2}\left[F_{bs}\left(C_{bs,in}-C_{bs,out}\right)+F_bC_b\right]\end{bmatrix}$$

Transfer functions of the control channels “inlet flow rate of concentrated biosurfactant – concentration of biosurfactant in outlet washing solution” ($W_{C_{bs,out}/F_b}(s)=\Delta C_{bs,out}(s)/\Delta F_b(s)$) and “flow rate of heating water – temperature of outlet washing solution” ($W_{T_{bs,out}/F_w}(s)=\Delta T_{bs,out}(s)/\Delta F_w(s)$), and the load disturbance channels “outlet flow rate of washing solution – concentration of biosurfactant in outlet washing solution” ($W_{C_{bs,out}/F_{bs}}(s)=\Delta C_{bs,out}/\Delta F_{bs}(s)$) and “outlet flow rate of washing solution – temperature of outlet washing solution” ($W_{T_{bs,out}/F_{bs}}(s)=\Delta T_{bs,out}/\Delta F_{bs}(s)$) are derived from the linearized equations (4). The following structure transfer functions are developed:

$$W_{C_{bs,out}/F_b}(s)=\frac{K_1(t_k)}{T_1(t_k)s+1}, \tag{5}$$

$$W_{C_{bs,out}/F_{bs}}(s)=\frac{K_2(t_k)}{T_1(t_k)s+1}, \qquad (6)$$

$$W_{T_{bs,out}/F_w}(s)=\frac{K_3(t_k)}{T_2^2(t_k)s^2+2T_2(t_k)\xi(t_k)s+1}, \qquad (7)$$

$$W_{T_{bs,out}/F_{bs}}(s)=\frac{K_4(t_k)(1+T_3(t_k)s)}{T_2^2(t_k)s^2+2T_2(t_k)\xi(t_k)s+1}, \qquad (8)$$

where

$$K_1(t_k)=\left(\frac{C_b}{F_{bs}}\right)\Bigg|_{t=t_k}, \qquad (9)$$

$$K_2(t_k)=\left(\frac{C_{bs,in}-C_{bs,out}}{F_{bs}}\right)\Bigg|_{t=t_k}, \qquad (10)$$

$$K_3(t_k)=\left(\frac{hS(T_{w,in}-T_{w,out})}{hSF_w+F_{bs}hS+F_{bs}F_w\rho c}\right)\Bigg|_{t=t_k}, \qquad (11)$$

$$K_4(t_k)=\left(\frac{(T_{bs,in}-T_{bs,out})(hS+F_w\rho c)}{hSF_w+F_{bs}hS+F_{bs}F_w\rho c}\right)\Bigg|_{t=t_k}, \qquad (12)$$

$$T_1(t_k)=\left(\frac{V}{F_{bs}}\right)\Bigg|_{t=t_k}, \qquad (13)$$

$$T_2(t_k)=\left(\sqrt{\frac{\rho cVV_j}{hSF_w+F_{bs}hS+F_{bs}F_w\rho c}}\right)\Bigg|_{t=t_k}, \qquad (14)$$

$$T_3(t_k)=\left(\frac{\rho cV_j}{hS+F_w\rho c}\right)\Bigg|_{t=t_k}, \qquad (15)$$

$$\xi(t_k)=\left(\frac{hSV_j+F_{bs}\rho cV_j+hSV+F_w\rho cV}{2T_2(hSF_w+F_{bs}hS+F_{bs}F_w\rho c)}\right)\Bigg|_{t=t_k}. \qquad (16)$$

If parameters $K_\bullet(t_k)$, $T_\bullet(t_k)$ and $\xi(t_k)$ are updated on-line with the measured values of the state and disturbance variables, the above transfer functions follow time-changing static and dynamic characteristics of the controlled process under real-time operating conditions.

4. Control system and controller adaptation algorithms

Temperature of the outlet washing liquid is controlled using a feed-forward/feed-back control scheme, in which the feed-forward controller compensates variations of the washing liquid flow rate.

Concentration of biosurfactant is not measured and can be only indirectly estimated in the inlet washing liquid using pH measurements and, therefore, the feedback control scheme can not be applied for the biosurfactant concentration control. The biosurfactant concentration in the outlet washing liquid is controlled by a feed-forward control scheme by which variations of the washing liquid flow rate and the biosurfactant concentration in the inlet washing liquid are compensated.

The block-scheme of the control system is presented in Figure 2.

The biosurfactant concentration set-point tracking controller realizes the transfer function

$$W_{RC}(c)=\frac{1}{W_{C_{bs,out}/F_b}(s)} \qquad (17)$$

and the respective discrete incremental algorithm is

$$F_b(t_k)=F_b(t_{k-1})+\Delta F_b(t_k), \qquad (18)$$

$$\Delta F_b(t_k)=\frac{1}{C_b(t_k)}\cdot$$

$$\left(\Delta C_{bs,set}(t_k)F_{bs}(t_k)+\frac{V(t_k)}{DT}\left(\Delta C_{bs,set}(t_k)-\Delta C_{bs,set}(t_{k-1})\right)\right),$$

$$\Delta C_{bs,set}(t_k)=C_{bs,set}(t_k)-C_{bs,set}(t_{k-1}).$$

Dynamics of the control channel "flow rate of heating water – temperature of outlet washing solution" is described by a 2nd order model (7), therefore, the PID control algorithm is adequate for the temperature control. Incremental form of the PID algorithm is as follows:

$$F_w(t_k)=F_w(t_{k-1})+K_g(t_k)$$
$$\left(e(t_k)c_1(t_k)-e(t_{k-1})c_2(t_k)+e(t_{k-2})c_3(t_k)\right), \qquad (19)$$

$$c_1(t_k)=1+\frac{T_d(t_k)}{DT}+\frac{DT}{T_i(t_k)},$$

$$c_2(t_k)=1+\frac{2T_d(t_k)}{DT},$$

$$c_3(t_k)=\frac{T_d(t_k)}{DT},$$

where $F_w(t_k)$ is PID control action, $e(t_k)$ is deviation of the controlled temperature from the set point value, $e(t_k)=T_{bs,set}-T_{bs,out}(t_k)$, DT is time discretization interval, $DT=t_k-t_{k-1}$, $K_g(t_k)$, $T_i(t_k)$ and $T_d(t_k)$ are controller parameters, determined by tuning rules at time t_k.

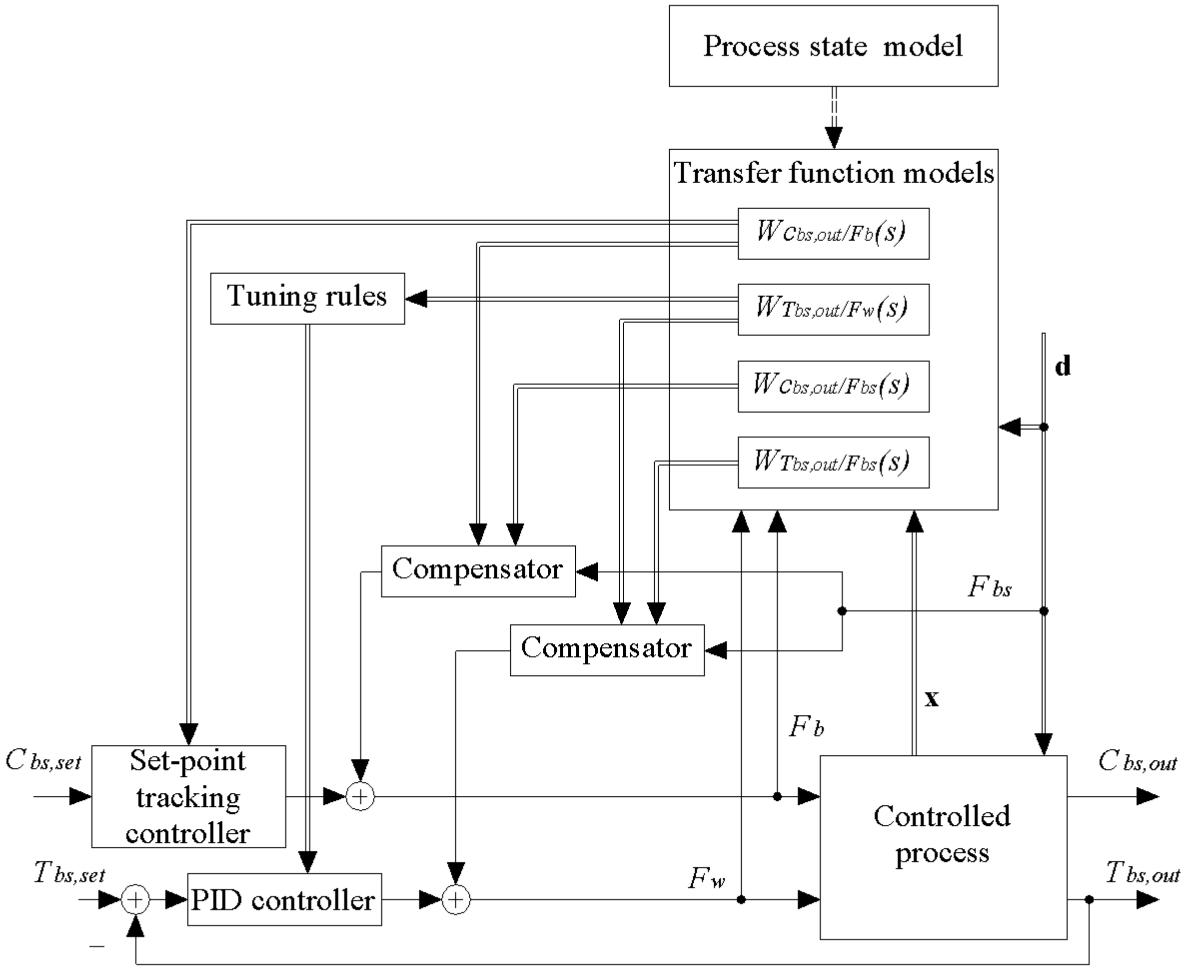

Figure 2. Block-scheme of the control system

For on-line adaptation of the PID controller we apply the Internal Model Control tuning rules [5]:

$$K_g(t_k)=\frac{2\xi(t_k)T_2(t_k)}{T_f K_3(t_k)}, \tag{20}$$

$$T_i(t_k)=2\xi(t_k)T_2(t_k), \tag{21}$$

$$T_d(t_k)=\frac{T_2(t_k)}{2\xi(t_k)}, \tag{22}$$

where $K_g(t_k)$, $T_i(t_k)$ and $T_d(t_k)$ are the PID controller parameters, T_f is the filter time constant (in simulation experiments T_f = 0.2 h).

The load disturbance compensators realize the transfer functions:

$$W_{KC}(s)=-\frac{W_{C_{bs,out}/F_{bs}}(s)}{W_{C_{bs,out}/F_b}(s)}=-\frac{K_2(t_k)}{K_1(t_k)}, \tag{23}$$

$$W_{KT}(s)=-\frac{W_{T_{bs,out}/F_{bs}}(s)}{W_{T_{bs,out}/F_w}(s)}= -\frac{K_4(t_k)(1+T_3(t_s)s)}{K_3(t_k)}, \tag{24}$$

where W_{KC} and W_{KT} denote transfer functions of the feed-forward controllers (compensators) of the biosurfactant concentration and the temperature, respectively.

An incremental compensation algorithm based on the transfer function W_{KC} is as follows:

$$F_b(t_k)=F_b(t_{k-1})- \frac{K_2(t_k)}{K_1(t_k)}\left(F_{bs}(t_k)-F_{bs}(t_{k-1})\right), \tag{25}$$

An incremental compensation algorithm based on the transfer function W_{KT} is as follows:

$$F_w(t_k) = F_w(t_{k-1}) - \frac{K_4(t_k)}{K_3(t_k)} \left(T_3(t_k) \frac{\Delta F_{bs}(t_k) - \Delta F_{bs}(t_{k-1})}{DT} + \Delta F_{bs}(t_k) \right), \quad (26)$$

$$\Delta F_{bs}(t_k) = F_{bs}(t_k) - F_{bs}(t_{k-1}).$$

5. Simulation of the control system performance

Performance of the control system (Figure 2) has been investigated via computer simulation using MATLAB and SIMULINK tools. The controlled process is simulated by model equations (1)-(3). The control actions of the controllers and the load disturbance compensators are calculated using the control algorithms (18), (19), (25) and (26). Responses of the control system are investigated for the set-point changes and the load disturbances.

In Figures 3, 4 reactions of the self-tuning control system to the step set-point changes are given. Responses of the controlled variables: biosurfactant concentration and temperature of washing solution are represented in Figures 3a, 4a, respectively, time trajectories of the respective manipulated variables (flow rates of the concentrated biosurfactant and heating water} are shown in Figures 3b, 4b. Time trajectories of the gain-scheduled PID controller parameters are shown in Figures 4c, d, e. For comparison, responses of the ordinary control system with constant controller parameter values are presented (dotted lines). According to the simulation results, applying of the proposed self-tuning control system provides significant improvement of the set-point tracking accuracy.

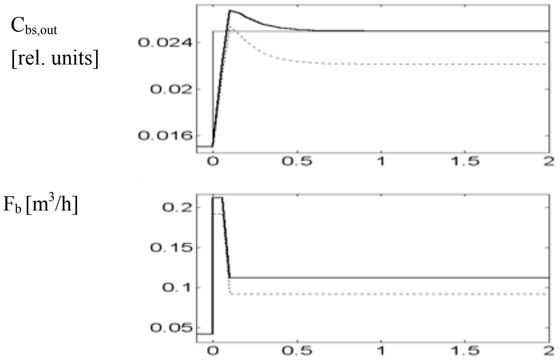

Figure 3. Response of the self-tuning control system to a step set-point change of the biosurfactant concentration from 0.015 to 0.025 rel.units at 7 m^3/h flow rate of washing liquid (solid lines). Response of the ordinary control system (dotted lines) is calculated for the set-point tracking controller with constant parameter values that are calculated for 5 m^3/h flow rate

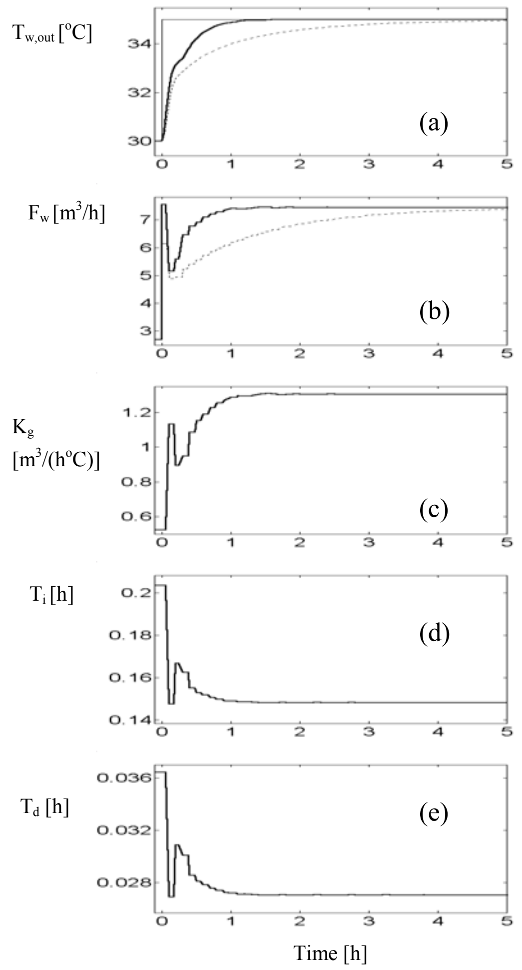

Figure 4. Response of the self-tuning control to a step set-point change of the washing liquid temperature from 30 °C to 35 °C at 7 m^3/h flow rate of washing liquid. Response of the ordinary control system (dotted lines) is calculated for the PID controller with constant parameters that are calculated for 5 m^3/h rate

In Figures 5, 6 respective graphs of the self-tuning control system reaction are given for the step load disturbance. Performance of the self-tuning algorithms is illustrated by the time trajectories of the biosurfactant concentration compensator parameters presented in Figures 5c, d, and the time trajectories of the PID controller and the temperature compensator parameters presented in Figures 6c, d, e and Figures 6f, g, h, respectively. For comparison, responses of the feed-forward/feed-back control system and the feed-back control system with constant controller and compensator parameter values, that are optimal for nominal technological regime, are given (dashed lines in Figures 5a, b, 6a, b). As it is demonstrated, the ordinary open-loop control of the biosurfactant concentration does not ensure compensation of the load disturbance caused deviation from the set-point value, and self-tuning of the disturbance compensator allows to improve performance of the open loop control system. In addition, the proposed self-tuning control system provides faster compensation of the temperature deviation compared to that in the ordinary control systems.

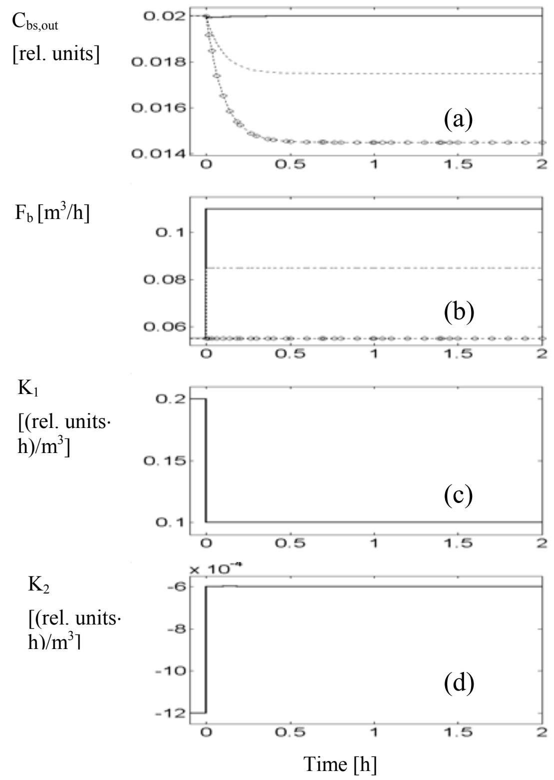

Figure 5. Response of the self-tuning control system operating at 0.02 rel. units biosurfactant concentration set-point to a step change of the washing liquid flow rate from 5 m^3/h to 10 m^3/h (solid lines). Responses of the ordinary feed-forward/feed-back control system (dotted lines) and the ordinary feed-back control system ("o"-dotted lines) are calculated for the controllers with constant parameter values that are calculated for 0.015 rel. units set-point value

6. Conclusions

The objective of this article was to develop a self-tuning control system for the control of contaminated soil washing technological process. To achieve this goal we used a feed-forward/feedback control scheme and a method of the controllers and the disturbance compensators adaptation, which is an extension of a recently developed method of the linear controller gain scheduling for nonlinear process control. The proposed procedure for development of the self-tuning control algorithms requires constructing the process state model and the model-based transfer functions of the control and the disturbance channels. Self-tuning of the controller and the compensator parameters is based on the transfer functions that are up-dated on-line with the measured values of the state and the disturbance variables.

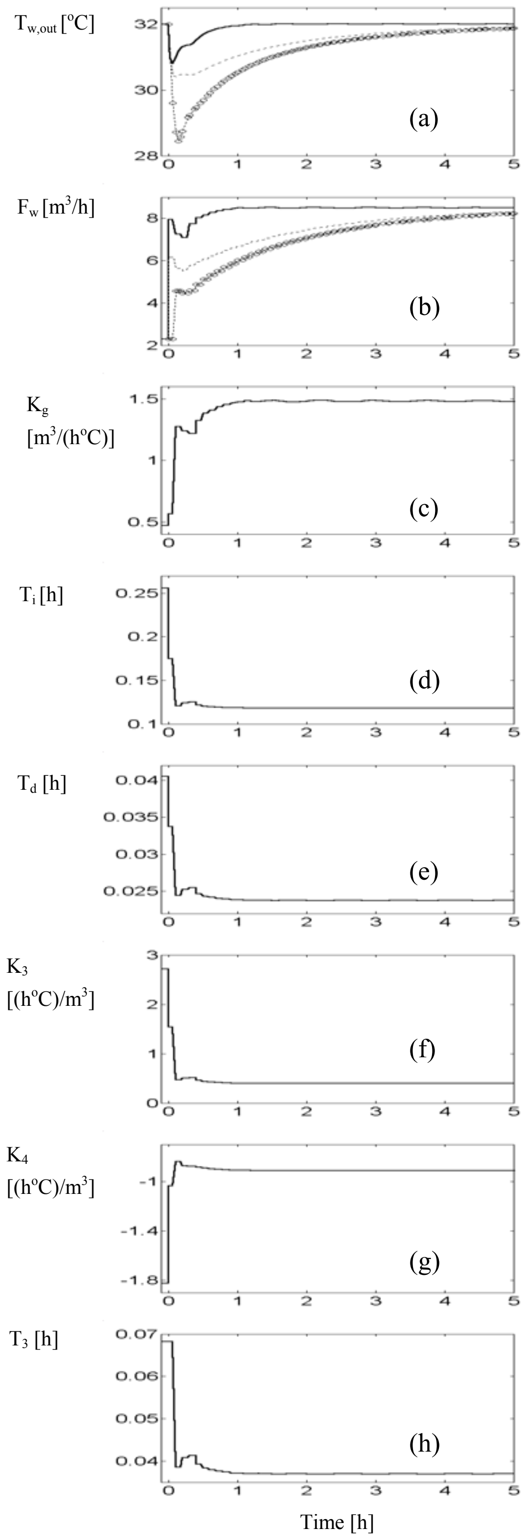

Figure 6. Response of the self-tuning control system operating at 32 ^{0}C biosurfactant temperature set-point to a step change of the washing liquid flow rate from 5 m^3/h to 10 m^3/h (solid lines). Responses of the ordinary feed-forward/feed-back control system (dotted lines) and the ordinary feed-back control system ("o"-dotted lines) are calculated for the controllers with constant parameter values that are calculated for 30 ^{0}C set-point value

In this article, the state model and the transfer functions of the contaminated soil washing technological process were constructed and the self-tuning control algorithms were developed. The simulated examples demonstrate that the proposed control system ensures fast adaptation of the compensator and the controller parameters, robust behavior under process state changes and significant improvement of the control performance compared to that in the conventional feed-forward/feed-back and feed-back control systems.

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