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ADAPTIVE CONTROL OF TEMPERATURE FOR MINIMIZATION OPERATING COSTS OF INDUSTRIAL METHANE TANK PROCESS

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Abstract. An algorithm for adaptive control of temperature in methane tank is developed in order to minimize operating costs under variation of the methane tank process conditions. The adaptation is based on process model and on-line minimization of objective function that relates operating costs to the process variables. Mathematical model for prediction of biogas production and simulation of the temperature control process is identified using experimental data from the waste water treatment plant. The temperature adaptive control system is investigated via computer simulation of the control system performance under operating conditions of real methane tank process during one year period. The process operating costs by optimal control of temperature are compared to those of temperature control at constant set-point. The model identification and the control system simulation results are presented and discussed.

Keywords: adaptive control; temperature; methane tank.

1. Introduction

Large-scale methane tanks operating in municipal sewage plants produce biogas through anaerobic digestion of sewage. Conversion of municipal sewage to biogas provides added value to sewage as an energy resource and reduces environmental problems associated with municipal wastewater. To improve performance and economy of methane-tank, an accurate control of biogas process is required [1].

In the anaerobic digestion process, a community of microbial species breaks down both complex and simple organic materials, ultimately producing methane and carbon dioxide. Anaerobic digestion can occur over a wide range of environmental conditions, although narrower ranges are needed for optimum operation. The factors that affect the rate of digestion and biogas production in methane-tanks include temperature, retention time, mixing of the digesting material, pH (self-regulating in most cases), water/solids ratio, etc. Among the above factors, the most important is temperature. By controlling temperature at narrow ranges, the desirable digestion process (mesophilic or thermophilic) can be realized. However, heating of industrial methane-tanks during colder periods is related to significant expenses of energy. The trade-off in maintaining optimum methane tank temperature to maximize biogas production while minimizing expenses is somewhat complex as the optimal level of temperature that provides minimum conversion cost can vary with changing external and internal conditions.

In this work, the temperature adaptive control system for minimization operating costs of the methane tank process is developed and investigated via computer simulation. The process model has been developed using experimental data from Kaunas wastewater treatment plant [2]. The simulation experiments of the control system performance are carried out using one-year observation data of the real process disturbances.

2. Methane tank process

The process of biogas production through anaerobic digestion takes place in an enclosed methane tank with attached heating and mixing systems (Figure 1). The continuous-type industrial methane tank has capacity of about 10000 m^3 and is fed by sludge stream at flow rate F_{in} and temperature T_{in}. Flow rate of an unloading effluent is (at steady state operating conditions $F_{out} = F_{in}$) and the biogas is produced at a rate F_g. The sludge circulating through the heat exchanger system at flow rate F_h (manipulated variable) maintains the methane tank process at operating temperature T_s. The energy for heating is supplied by water circulating through the heat exchanger at flow rate F_w and the inlet and outlet temperatures $T_{w,\,in}$ and $T_{w,\,out}$, respectively.

The heating energy required to keep up the temperature in methane tank depends on the temperature and flow rate of the inlet sludge and the outdoor temperature, which determines the heat losses through methane-tank wall. Due to variation of the above external parameters, the heating energy requirement can vary in a wide range during a cycle of the seasons.

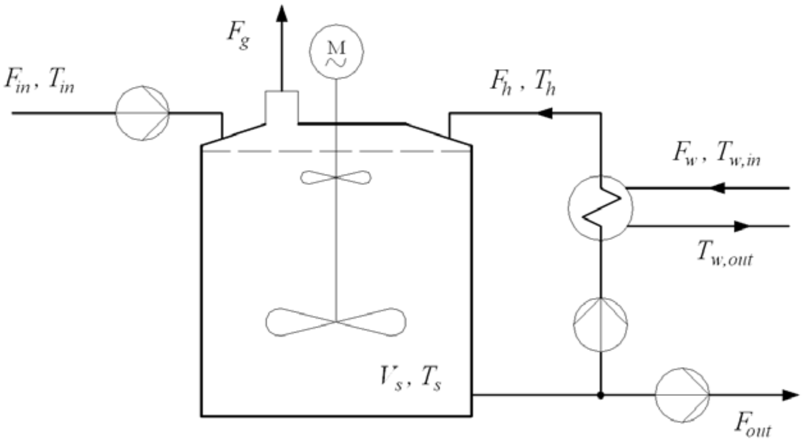


Figure 1. Methane tank system

3. Development of the control algorithm

The goal of the methane tank process control is to break down the major part of organic materials of the sludge at minimum cost price.

The methane-tank process can be controlled by manipulating the temperature and the retention time of sludge in methane tank. The retention time depends on the sludge flow-rate through methane tank and the volume of sludge:

$$t_{ret} = \frac{V_s}{F_{in}}, \tag{1}$$

where t_{ret} is retention time of the sludge in methane tank; F_{in} is volumetric flow rate of inlet sludge; V_s is volume of sludge in methane tank.

However, control of the flow rate or the volume is often not available in practice, as the volume of container for the inflowing sludge storage is usually small to accumulate large amounts of sludge, and the working volume of sludge in methane tank can vary in a narrow range. Therefore, the retention time usually is not controlled and depends on the load of methane tank (volumetric flow rate of inlet sludge). Thus, the industrial methane tank process is usually controlled by manipulating only the temperature of sludge.

Our strategy of temperature control of the anaerobic digestion process is to pursue simultaneously the two objectives: breaking down the desired percentage of organic materials of sludge and minimizing of the cost price of methane tank process under varying technological conditions. Therefore, an algorithm for calculation of the temperature set-point consists of two steps. At the 1st step, meeting of the demand to decompose the organic materials to desired percentage is estimated. At the 2nd step, the temperature set-point is calculated in order to minimize the cost price of the digestion process while breaking down the desired percentage of organic materials.

Realization of the temperature adaptation algorithm is based on prediction of the digestion process under various operating conditions.

Prediction of the digestion process

For prediction an intensity of the digestion process at various flow rates of inlet sludge and temperatures in methane tank, the functional relationship is required that relates the biogas production with the above parameters. The functional relationship can be identified using experimental data of batch digestion process experiments, at which the samples of sludge are tested.

The identification procedure consists of the following steps:

1. Carrying out of the digestion process experiments at various levels of temperature $\theta_{s,i}$ (i = 1, ..., n, n is the number of temperature levels) from the range, at which the mesophilic bacteria's growth and activity occurs (32-40 °C).

During the experiments, the biogas production rate $F_{g,\theta i}$ in the sludge volume unit at time points t_j (j = 1, ..., m, m is the number of points) is measured. The processes are carried out until production of biogas terminates.

2. Approximation of the experimental points by a relevant functional relationship.

In this work, functional relationship of the following structure was applied that suits well for approximation of the experimental curves:

$$F_g(\theta_s, t) = \sum_{k=0}^{p} a_k(\theta_s) t^k, \tag{2}$$

where $F_g(\theta_s, t)$ is the biogas production rate in the volume unit at temperature θ_s at time point t of batch digestion process; $a_k(\theta_s)$ are parameters identified as functions of the process temperature:

$$a_k(\theta_s) = \sum_{i=0}^{n} \alpha_{ki}\theta_s^i), \quad (3)$$

where α_{ki} are parameters.

The parameters a_k and α_{ki} are identified using the least squares method [3] and experimental data obtained at the 1st step.

The total amount of biogas produced in batch processes in the volume unit is estimated by integrating the equation (2):

$$Q_g(\theta_s,t) = \int_0^t F_g(\theta_s,t)dt = \sum_{k=0}^{p} a_k(\theta_s)\frac{t^{k+1}}{k+1}. \quad (4)$$

3. Calculation a paired set of ultimate values of the interrelated variables θ and *t*, at which the desired percentage of organic materials is broken down (the desired part of the maximum amount of biogas available from the investigated sludge is obtained).

The above isoline is calculated using the equation (4), in which the produced biogas is fixed at the desired value:

$$\eta Q_{g,\max} = \sum_{k=0}^{p} a_k(\theta_{su})\frac{t_u^{k+1}}{k+1}, \quad (5)$$

where $Q_{g,\max}$ is the maximum amount of biogas available from a volume unit of the investigated sludge, estimated at the 1st step; η is a desired percentage of the maximum amount of biogas;

θ_{su} and t_u are interrelated ultimate values of temperature and process duration, respectively, at which the desired percentage of maximum amount of biogas is produced.

The equation (5) is further applied for prediction of the continuous methane tank process by replacing the batch process time *t* with the retention time of sludge in methane tank t_{ret} (1).

4. Evaluation of the continuous digestion process in methane tank.

The ultimate rate of biogas production at the retention time t_{ret} given by (1) is estimated using the equation

$$F_{gu} = \frac{\eta Q_{g,\max}}{t_{ret}}V_s = \eta Q_{g,\max}F_{in}. \quad (6)$$

Calculation of the temperature set-point

The temperature set-point variation is based on comparison of the estimated ultimate rate F_{gu} with the measured rate F_{gm} of biogas production:

1. If $F_{gm} \le F_{gu}$, the biogas production rate is to be increased by raising the process temperature up to the upper permissible level.

The required increment of temperature can be predicted by estimating the ultimate value of temperature corresponding to the current retention time (equations (1) and (4)).

2. If $F_{gm} \ge F_{gu}$, the demand to decompose the organic materials to desired percentage is satisfied and the temperature set-point is calculated to minimize the cost price of the methane tank process.

The main expenses of the biotechnological process realization in methane tank are related with the cost of energy for stirring and keeping up the temperature of sludge. The cost price of the energy is partially compensated by a profit from the sold biogas.

For solving the optimization problem of the methane tank process, the following objective function (performance index) is applied:

$$J = C_{stir} + C_{temp} - C_{gas} \to min, \quad (7)$$

where C_{stir} is the cost per time unit of energy for the stirring; C_{temp} is the cost per time unit of energy for keeping up the temperature of sludge; C_{gas} is the cost of biogas produced in methane tank per time unit.

The terms in formula (7) are related to the controllable technological parameters according to the following functional relationships:

$$C_{stir} = p_e P_m, \quad (8)$$

where p_e is the cost of electric power; P_m is the power of the stirrer motor.

$$C_{temp} = p_h \frac{A_m h(\theta_s - \theta_o) + F_{in}\rho_s c_s(\theta_s - \theta_{in})}{\eta_{he}}, \quad (9)$$

where p_h is the cost of energy for heating; θ_s is the temperature of sludge in methane tank; θ_o is the outdoor temperature; θ_{in} is the temperature of inflowing sludge; F_{in} is the volumetric flow rate of inflowing sludge; A_m is the methane-tank surface area; *h* is the heat transfer coefficient through the methane tank wall; ρ_s is density of sludge; c_s is the specific heat capacity of sludge; η_{he} is efficiency of the heat exchanger.

$$C_{gas} = p_g V_s F_{gc}(\theta_s, t_{ret}), \quad (10)$$

where p_g is the cost of biogas per volume unit; $F_{gc}(\theta_s, t_{ret})$ is the biogas production rate in the continuous methane tank process in the volume unit of sludge. Prediction of the biogas production rate refers to the equation (4), in which the process time corresponds to the retention time of sludge in the continuous operating mode methane tank:

$$F_{gc}(\theta_s, t_{ret}) = \frac{Q_g(\theta_s, t_{ret})}{t_{ret}} = \sum_{k=0}^{p} a_k(\theta_s)\frac{t_{ret}^k}{k+1}. \quad (11)$$

At each time discretization point of the process optimization, the optimal temperature set-point value is determined, at which the minimum value of the objective function (7) is gained. When the above set-point control action is applied, a real alteration of the objective function is to be estimated using the measured values of process parameter at the new steady state operating point, and the control correction is to be applied if necessary.

Block-scheme of the temperature set-point optimal control algorithm is presented in Figure 2.

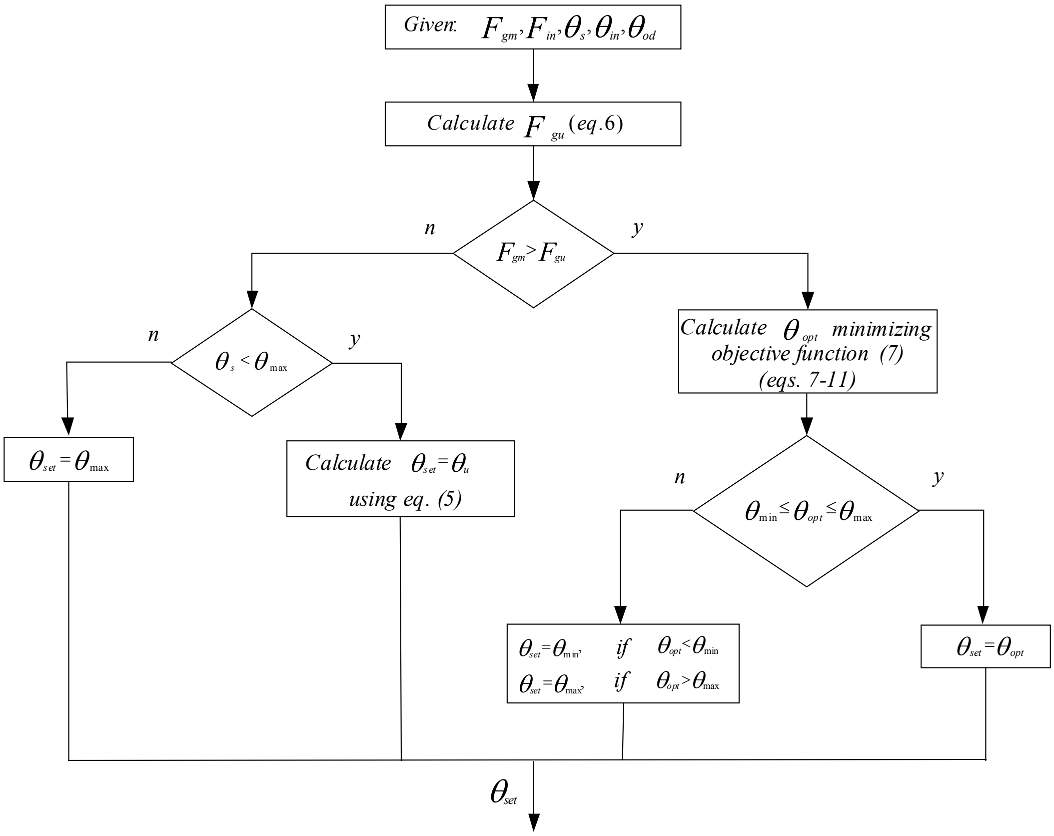


Figure 2. Block-scheme of the temperature set-point control algorithm

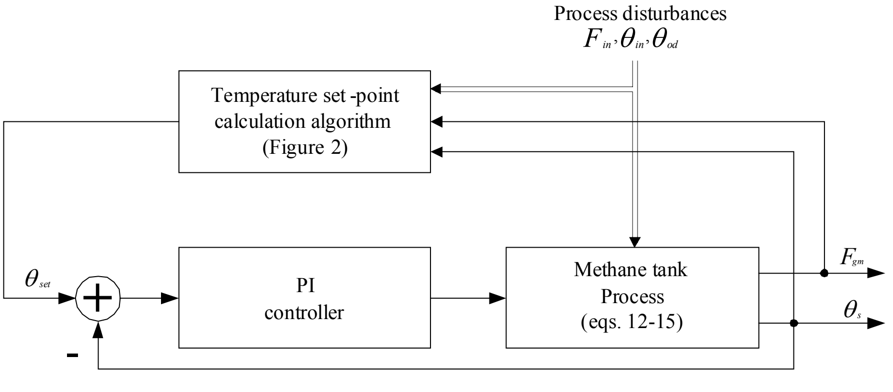


Figure 3. Block-scheme of the temperature optimal control system

4. Simulation of the control systems performance

Performance of the temperature control system was investigated via computer simulation implemented in the Matlab/Simulink environment.

The block-scheme of the simulated system is presented in Figure 3.

Mathematical model of the methane tank process

The methane-tank process can be described by energy balance equations for the methane-tank and the heat exchanger. Assuming that the heat exchange can be considered as a lumped parameter process and accumulation of energy in the heat exchanger is negligible, the energy balance-based state equations of the variables θ_s, θ_h, $\theta_{w,out}$ are the following:

$$\dot{\theta}_s = \frac{F_h}{V_s}(\theta_h - \theta_s) - \frac{F_{in}}{V_s}(\theta_s - \theta_{in}) - \frac{A_m h_m}{V_s \rho_s c_s}(\theta_s - \theta_{od}), \quad (12)$$

$$\dot{\theta}_h = \frac{A_h h_h}{V_{hs} \rho_s c_s}(\theta_{w,out} - \theta_h) - \frac{F_h}{V_{hs}}(\theta_h - \theta_s), \quad (13)$$

$$\begin{aligned} \dot{\theta}_{w,out} &= \frac{F_w}{V_w}(\theta_{w,in} - \theta_{w,out}) - \\ &- \frac{A_h h_h}{V_w \rho_w c_w}(\theta_{w,out} - \theta_h) - \frac{E_{L,W}}{V_w \rho_w c_w} \end{aligned}, \quad (14)$$

$$\dot{F} = \frac{1}{T}\left(V_s F_{gc}(\theta_s, t_{ret}) - F\right), \quad (15)$$

$$F_{gc}(\theta_s, t_{ret}) = \sum_{k=0}^{p} a_k(\theta_s) \frac{t_{ret}^k}{k+1},$$

$$t_{ret} = V_s / F_{in},$$

where θ_s is temperature in the methane-tank, θ_h is temperature of heated sludge in the outlet of heat exchanger, $\theta_{w,out}$, $\theta_{w,in}$ are outlet and inlet temperatures of heating water, θ_{in} is temperature of inlet sludge, θ_{od} is outdoor temperature, F is biogas production rate, F_{gc} is biogas production rate in the volume unit of sludge at steady state operating conditions, F_h is sludge volumetric flow rate through heat exchanger, F_{in} is volumetric flow rate of inlet sludge, F_w is volumetric flow rate of water through heat exchanger, T is time constant, V_s is volume of sludge in methane-tank, V_{hs}, V_w are volumes of sludge and water in heat exchanger, A_m is methane-tank surface area, A_h is heat transfer area of heat exchanger, h_m is heat transfer coefficient over methane-tank surface, h_h is heat transfer coefficient through heat exchanger wall, c_s, c_w are specific heat capacities of sludge and water, ρ_s, ρ_w are densities of sludge and water, and $E_{L,W}$ is heat loss over heat exchange surface.

The other factors of energy balance in methane-tank, the heat of biochemical reactions and stirring energy are neglected because they are small compared with the other terms of the balance equations.

The heat transfer rates $A_h h_h$, $A_m h_m$ and the heat loss $Q_{L,W}$ were estimated using observation data of the industrial methane tank at steady state operating conditions. The time constant T is estimated using observation data at transient conditions.

Parameters of equations (2), (3), (15) have been identified using experimental data of 3 batch digestion process experiments, realized at different temperatures (32 ^{o}C, 37 ^{o}C, 40 ^{o}C). In Figure 4, the experimental data and their approximation by the identified 8th order ($k = 8$) functional relationships (2) are presented.

Parameters of the model equations (12)-(15) are given in Table 1.

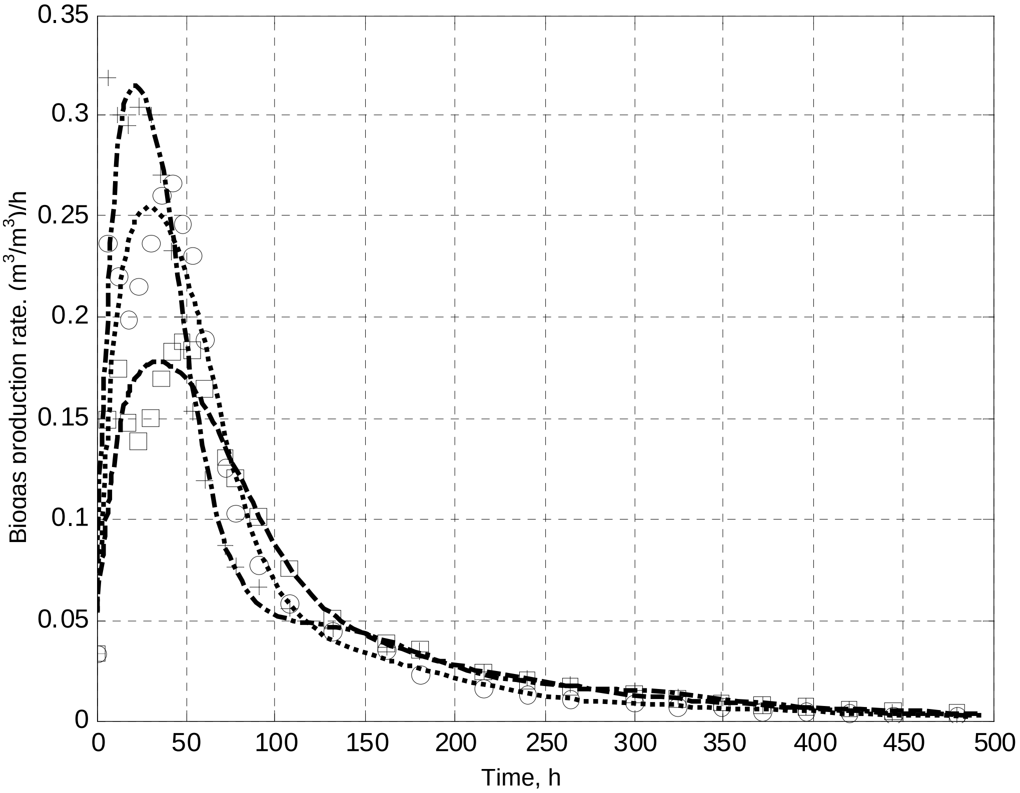


Figure 4. Experimental data (points) and the model-based approximation (lines) of biogas production at various temperatures (□ – $\theta = 32$ ^{0}C, ○ – $\theta = 37$ ^{0}C, + – $\theta = 40$ ^{0}C)

Table 1. Values of the model (12)-(15) parameters

Physical constants	Constructive parameters	Estimated parameters	
$c_s = 4180$ J/(kg ^{o}C)	$V_s = 8800$ m^3	$A_h h_h = 1{,}016 \cdot 10^9$ J/(h ^{o}C)	$h_m = 7{,}934 \cdot 10^3$ J/(m^2 h ^{o}C)
$\rho_s = 1000$ kg/m^3	$V_{hs} = 3.98$ m^3	$Q_{L,W} = 3{,}5 \cdot 10^6$ J/h	$T = 3$ h
$c_w = 4180$ J/(kg ^{o}C)	$V_w = 3.81$ m^3		
$\rho_w = 1000$ kg/m^3	$A_m =$ 2040 m^2		

Parameters of the equations (5)-(10) in simulation experiments are as follow: P_m=16 kW, $\eta = 0.60$, $\eta_{he} = 0.7$, $p_e = 0.18$ Lt/kWh, $p_h = 0.188$ Lt/kwh, $p_g = 0.63$ Lt/m^3. The retention time is estimated using mean value of the volumetric flow rate of inlet sludge from the moving window of 14 days length.

Feed-back controller

Transient responses of the process temperature to step changes of control variable (volumetric flow rate of sludge through heat exchanger) show that the resultant time delay is significantly smaller then the time constant, therefore, the PI control law is adequate for the feedback control. The velocity form of the discrete PI control algorithm is

$$u_{PI}(t_k) = u_{PI}(t_{k-1}) + \Delta u_{PI}(t_k), \qquad (16)$$

$$\Delta u_{PI}(t_k) = K_C \left(e(t_k)\left(1 + \frac{\Delta t}{T_I}\right) - e(t_{k-1}) \right), \qquad (17)$$

in which $u_{PI}(t_k)$ is control action of the PI controller, $\Delta u_{PI}(t_k)$ is an increment of the control action, $e(t_k)$ is deviation of the controlled temperature from the set-point value ($e(t_k) = \theta_s(t_k) - \theta_{set}(t_k)$), Δt is time discretization step of control actions, K_C and T_I are controller parameters.

The internal model control tuning rules [4] that demonstrate high performance of controller by tracking set-point changes are used for tuning the controller parameters:

$$K_C = \frac{2T_{pr} + \tau_{pr}}{K_{pr} T_f}, \quad T_f = 0.25 T_{pr}, \qquad (18)$$

$$T_I = T_{pr} + \tau_{pr}/2, \qquad (19)$$

where K_{pr}, T_{pr}, τ_{pr} are the process gain, resultant time constant and resultant time delay, respectively. The above parameters are estimated using simulation experiment of the controlled temperature response to the step change of sludge volumetric flow rate through heat exchanger (F_h) at nominal operating conditions ($F_{in} = 17$ m^3/h, $\theta_{in} = 17.6$ ^{0}C, θ_{od}=6.2 ^{0}C).

The estimated process dynamic parameters and the controller tuning parameters are given in Table 2.

Table 2.

Process dynamic parameters	PI controller tuning parameters
$K_{pr} = 0.89 \frac{^0C}{m^3/h}$, $T_{pr} = 8$ h, $\tau_{pr} = 2$ h;	$K_C = 10.1$, $T_I = 9$, $\Delta t = 2$ h .

For more accurate tracking of time-varying temperature set-point, the adaptive PI controller can be applied [5].

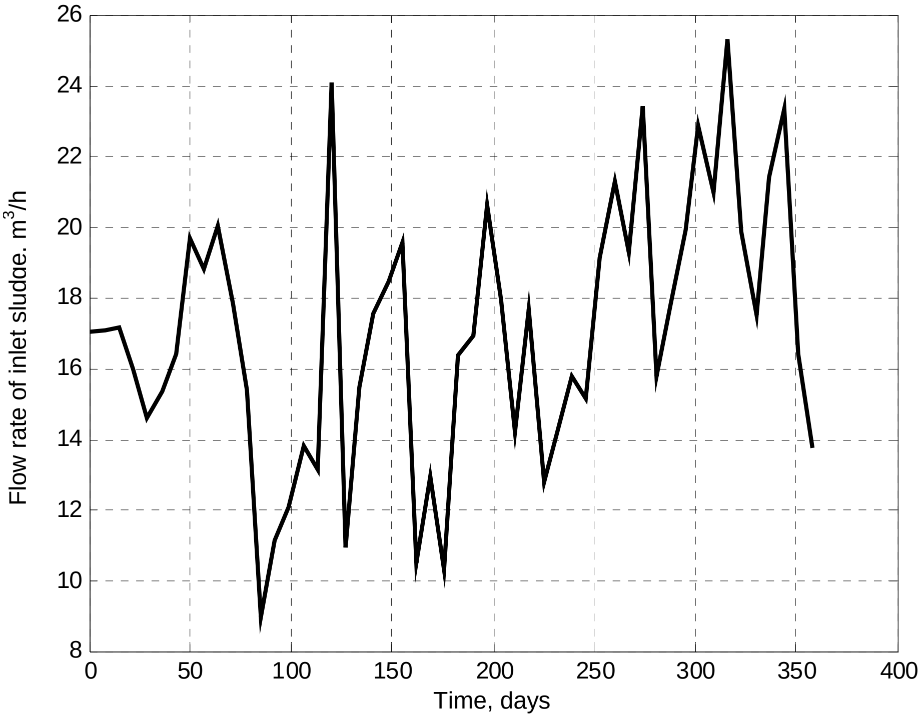
Simulation results

In the simulation experiments, the process disturbances (the volumetric flow rate of inlet sludge (F_{in}), the temperature of inlet sludge (θ_{in}), and the outdoor temperature (θ_{od})) were simulated using registered data of real disturbances of methane tank operating in Kaunas sewage plant. Variations of the above variables during one year time period are given in Figures 5a-c.

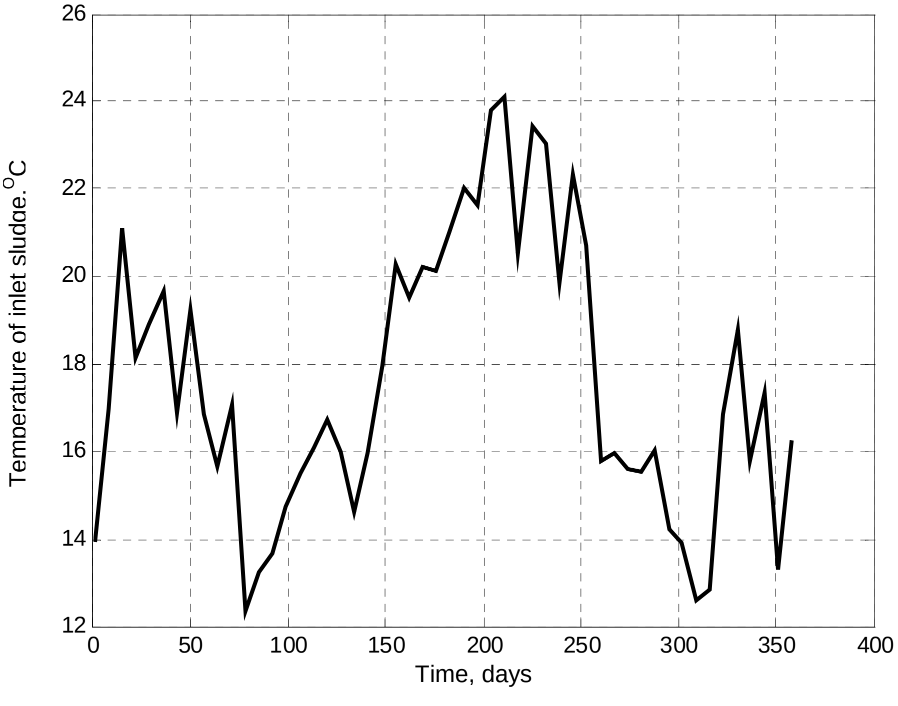
The performance of the proposed temperature control system minimizing the objective function (7) under the simulated disturbances is illustrated in Figure 5d. The presented variation of temperature demonstrates adaptation of temperature to the time-varying process variables. The dotted line in Figure 5d shows the temperature set-point ($\theta = 34.4$ ^{o}C), at which the temperature is controlled by ordinary control system according to technological schedule.

In Figure 5e, the simulated biogas production rate time trajectories by applying the adaptive control system and by controlling the process temperature at constant level are shown. The predicted percentages of organic material degradation by applying the adaptive control system and by controlling the process at predetermined constant temperature set-point are presented in Figure 5f.

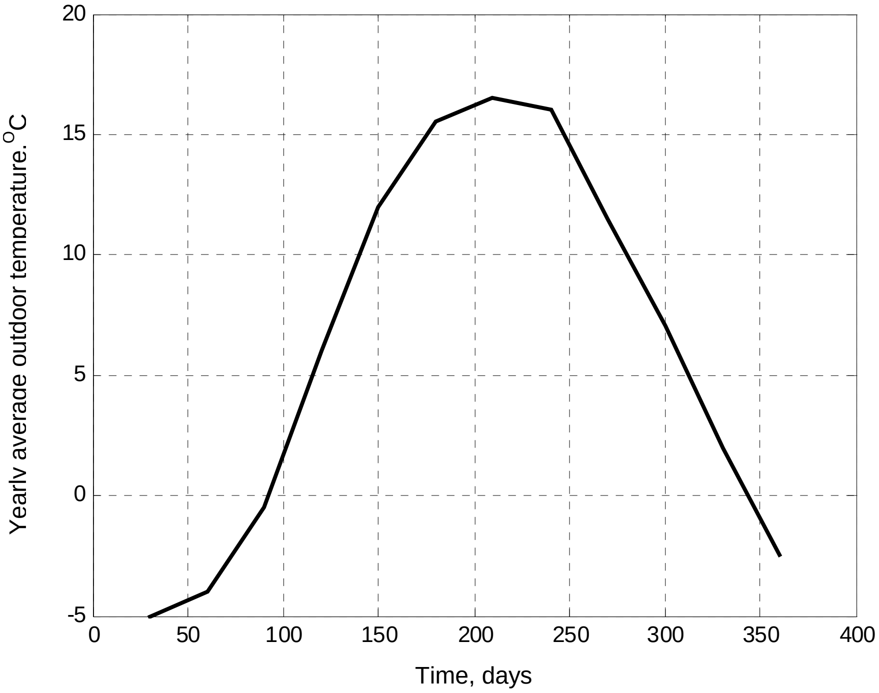
In Figure 5g, time trajectory of the objective function value at optimal control of the process temperature is presented. For comparison, the objective function time trajectory at constant temperature is shown by dotted line.


26
24
22
20
18
16
14
12
10
8
Flow rate of inlet sludge, m3/h
0
50
100
150
200
250
300
350
400
Time, days

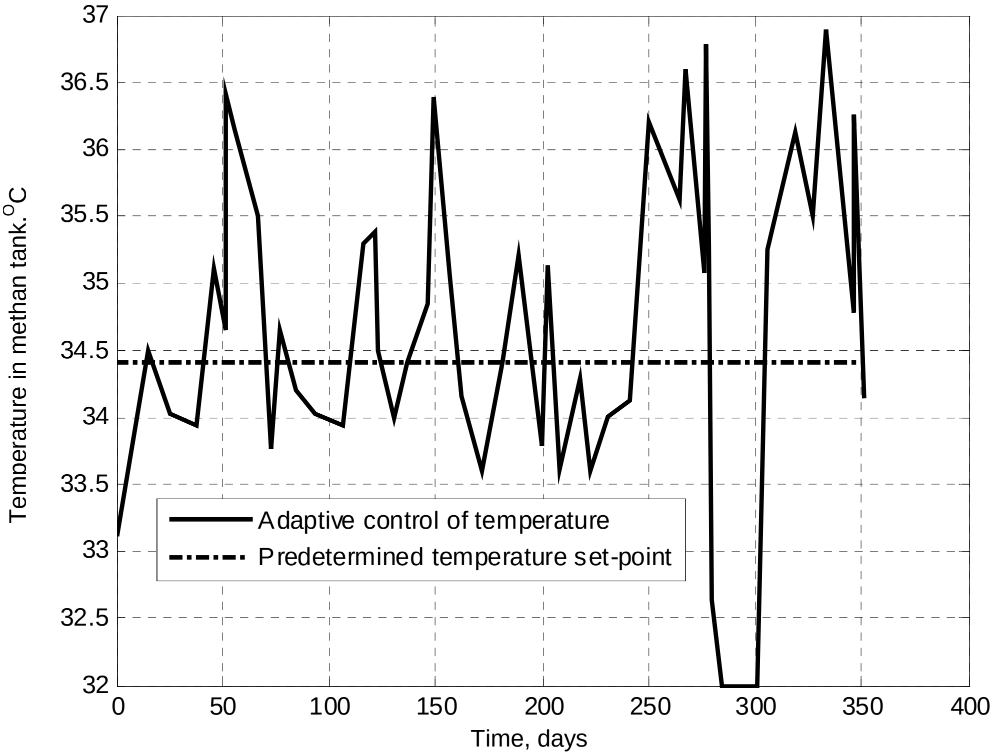
(a)


26
24
22
20
18
16
14
12
Temperature of inlet sludge, °C
0
50
100
150
200
250
300
350
400
Time, days

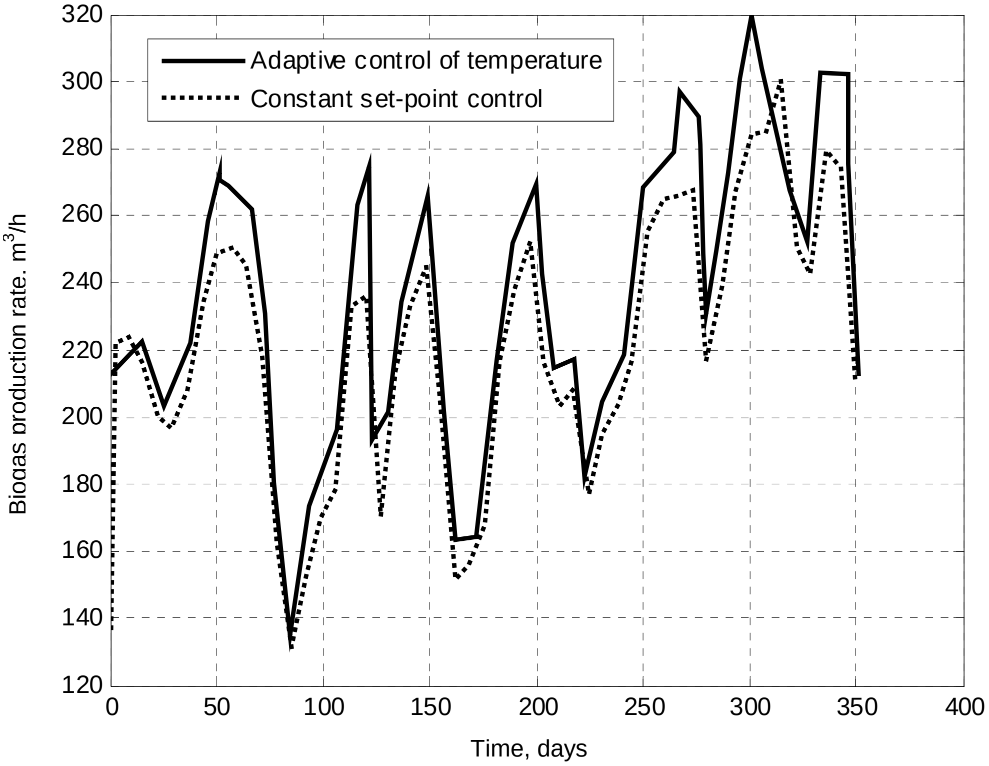
(b)


Yearly average outdoor temperature.^{O}C
20
15
10
5
0
-5
0
50
100
150
200
250
300
350
400
Time, days

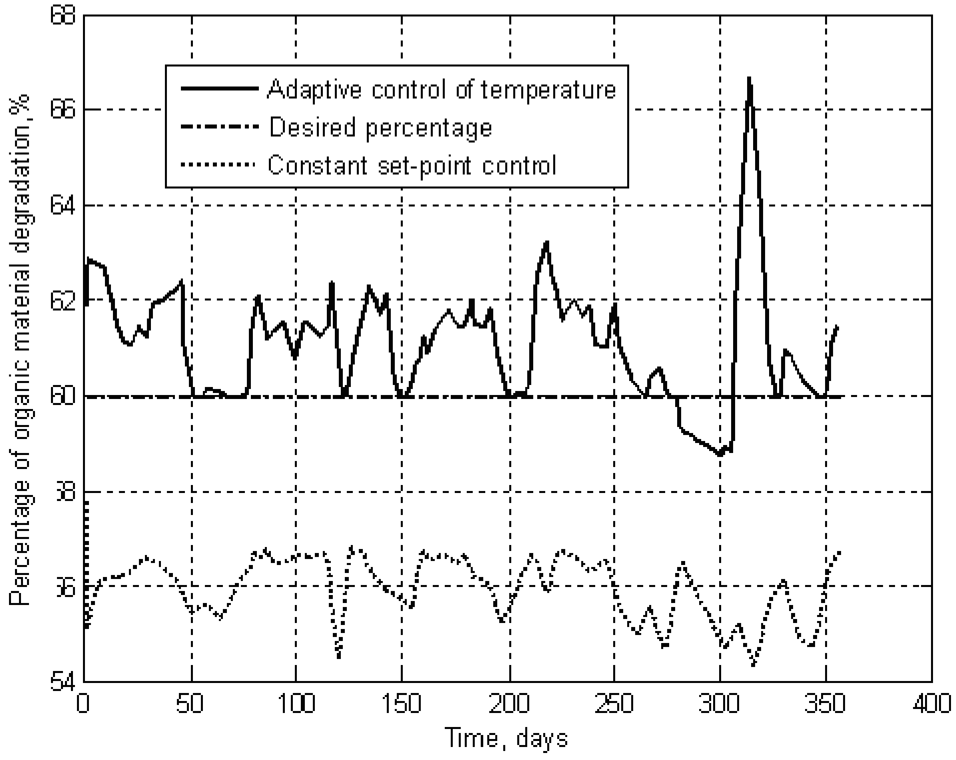
(c)


Temperature in methan tank.^{O}C
37
36.5
36
35.5
35
34.5
34
33.5
33
32.5
32
0
50
100
150
200
250
300
350
400
Time, days
Adaptive control of temperature
Predetermined temperature set-point

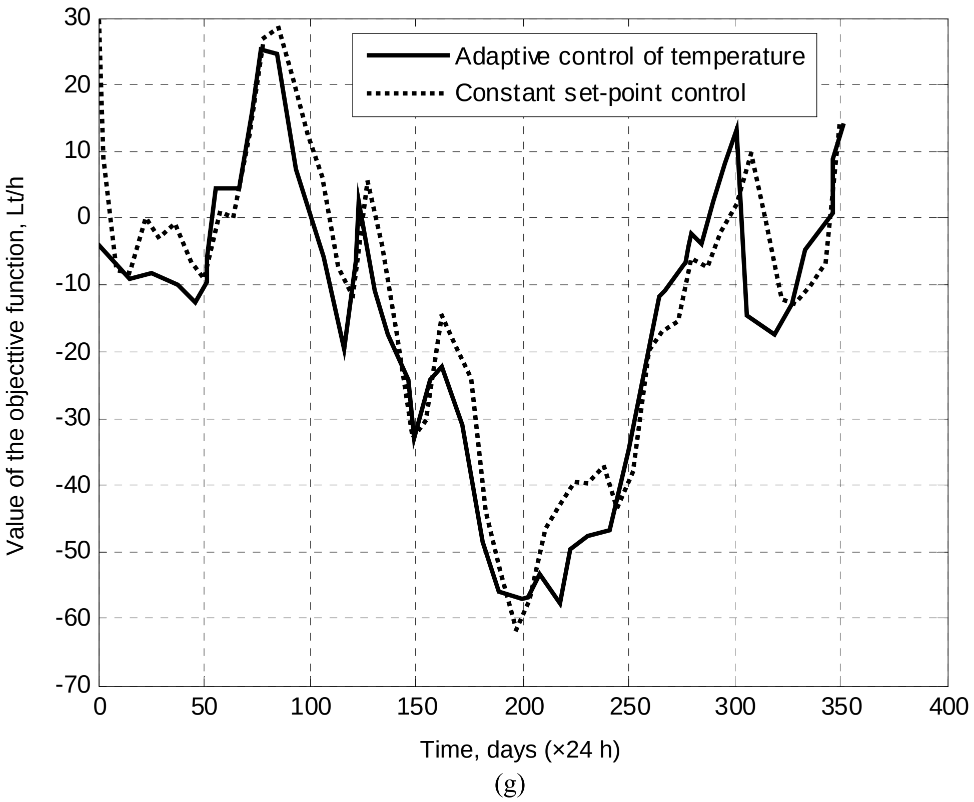
(d)


Adaptive control of temperature
Constant set-point control
Biogas production rate, m³/h
320
300
280
260
240
220
200
180
160
140
120
0
50
100
150
200
250
300
350
400
Time, days

(e)


Adaptive control of temperature
Desired percentage
Constant set-point control
Percentage of organic material degradation, %
68
66
64
62
60
58
56
54
0
50
100
150
200
250
300
350
400
Time, days

(f)



(g)

Figure 5. Simulation results of the control system performance

As it follows from the simulation results, the investigated control system copes with the main objectives of control: the biogas production rate is maintained to meet the requirement of the organic material degradation and the operating costs of the controlled process are reduced compared to that by keeping up the process temperature at constant set-point.

The estimated mean percentage of the organic material degradation by applying the adaptive control system totals 60.8 % (the lowermost desired percentage is 60 %). The estimated mean percentage at constant set-point control of temperature totals 56 %. It is by 7.9 % less compared to this by applying the adaptive control system.

In the simulation experiment, the yearly operating costs due to adaptive control of process temperature decrease for about 30 000 Lt.

5. Conclusions

In this paper, an adaptive control system of temperature is developed for minimization the operation costs of industrial methane tank process. The temperature adaptation is based on the on-line minimization of objective function that relates operation costs of digestion process with the process parameters: the outdoor temperature, the temperature of inlet sludge, the volumetric flow rate of inlet sludge and the biogas production rate. The biogas production rate is predicted using the identified functional relationship that relates biogas production with the process temperature and the retention time of sludge in methane tank.

Efficiency of the proposed control system is investigated via computer simulation of the control system performance under time-varying operating conditions of real methane tank process during one year period. The simulation results show noticeable decrease of operating costs while keeping the biogas production rate above the ultimate values. In the simulation experiment, the operating costs due to adaptive control of temperature are reduced by 30 000 Lt compared to those by controlling the temperature at constant level.

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