Optimal energy saving and management in antibiotics production

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Energy efficiency is a very important indicator in the stability assessment of industrial processes. The optimal utilization of energy is a vital task today, as it determines the state of environment, technology and product price. The present work describes a method for the reduction of energy consumption by heat integration, in a system of bioreactors for the production of antibiotics. A scheme for heat integration of two heat reservoirs is suggested, ensuring performance at different time intervals. A mathematical model of the processes taking place in the two reactors is developed. On the base of the model, a strategy for optimal control of energy resources using heat integration of two heat reservoirs is proposed. The optimization task is formulated in terms of the Mixed Integral Non-Linear Programming (MINLP). The proposed method is applied to a real industrial process for antibiotics production.

**Keywords:** Heat integration, batch reactors, Heat storages, Antibiotics

**INTRODUCTION**

There is a contemporary problem with efficient energy consumption. The energy sources are constantly decreasing and have a negative effect on the environment, thereby forcing the search for alternative resources.

In industrial systems, the optimal utilization of the energy resources is one of the main problems [1]. All up-to-date scientific achievements and engineering practices are involved in solving these problems as early as the design phase. In existing production lines, it is necessary to make the most of the energy using suitable engineering solutions.

In most of the chemical and biochemical productions, a number of heating and cooling processes are usually involved according to the technological scheme [2, 3]. They most often result in major energy losses. The production of antibiotics is one of such processes [4]. In this case, one could effectively decrease, as well as control, the energy consumption, using the approach of heat integration of the production processes.

**AIM**

The aim of the present work is to suggest a practical method for energy saving by heat integration of a system of bioreactors in the production of antibiotics, using heat reservoirs and their control methods. Thus, the costs of energy resources could be decreased.

**PROBLEM DESCRIPTION**

A bioreactor system for the production of antibiotics was studied. The process involves preparation of a nutrient, followed by its sterilization and cooling to working temperature for the fermentation process. The nutrient preparation and its sterilization involve the use of water vapor as an energy carrier. The fermentation is performed after cooling the sterilized nutrient to working temperature of 30°C. Technical and cooled water is used for this process. The idea for reduction of energy consumption is to integrate these two processes. If a certain reactor is in a regime of cooling, then the energy released could be stored in a heat reservoir to be used for the preparation of nutrients in another reactor. This would save energy in the second reactor, and also reduce the amount of technical water required for these processes. The idea can be implemented by designing a proper scheme. Furthermore, the major factors providing maximum utilization of the internal energy in both reactors should be determined.

Figs. 1 (a) and (b) show such a scheme for running the processes. The determination of the controlling factors is reduced to the parameters of the time intervals. The process conditions should provide a minimum value of the energy used by the external systems.
PRODUCTION OF ANTIBIOTICS

One of the most common methods used for the production of antibiotics is the preparation of the substrate by fermentation. It is carried out in bioreactors, and the sequence of processes and their conditions are listed below:

Stage 1: Nutrient preparation

1. This process is carried out by mixing micelles and nutrient in a subsidiary reactor.

Stage 2: Fermentation components

1. Mixing of component \( V_1 \) from Tank A with \( V_{21} \) with water at 20°C (CW20) by stirring for 1 hour until nutrition medium NMA is obtained.
2. Mixing of component \( V_1 \) from Tank B with \( V_{22} \) CW20 by stirring for certain time until nutrition medium NMB is obtained.

Stage 3: Fermentation process

1. Transfer of NMA to reactor \( F_C \) and heat from 20°C to 55°C.
2. Heating NMA from 55°C to 100°C using steam.
3. Sterilization of NMA with 100°C steam for about 0.5 hours.
4. Transfer of NMB to \( F_C \) and mixing it with NMA to obtain AB_IAB.
5. Addition of \( V_{35} \), CW20.
6. Heat the mixture \( V_C \) with vapor to \( T = 55°C \) to obtain medium NMAB.
7. Heat the mixture NMAB with water vapor from 55°C to 120°C.
8. Sterilization of NMAB with water vapor at temperature of 120°C.
9. Cooling NMAB from 120°C to 45°C using CW20.
10. Cooling of NMAB from 45°C to 30°C using 5°C cooled water (CW5).
11. Addition of IMX to NMAB up to volume \( V_{\text{max}} \) to obtain FM.
12. Cooling the medium FM to \( T_{\text{fer}} \) using CW5 and carry out fermentation for 120 h – 150 h until the product FB is obtained.

Stage 4: Dilution

1. Transfer FB to an intermediate reservoir.
2. Addition of \( V_d \) with water CW20 for deactivation to obtain the product DFB.

Stage 5: Filtration

1. Filtering the DFB to obtain concentrated material DSC.

Stage 6: Sterilization of the empty fermenter

1. Washing the empty fermenter with CW20.
2. Sterilization of the washed fermenter with water vapor with temperature of 130°C.
3. Sterilization of the washed fermenter with water vapor with temperature of 130°C.

PROCESS ORGANIZATION

According to the technology (Stages 1-6), there are a number of processes requiring the use of external energy (STEAM, CW20, CW5) for heating and cooling. The problem with their dependence on external energy sources can be solved by creating conditions for heat integration. In Fig.1, the “H” reactor will be regarded as the fermenter, where the processes 3.1–3.7 have ended. By the end of 3.7, the mixture in the fermenter would have a temperature of \( T_{\text{fer}} = 120°C \). Processes 3.8 and 3.9 are carried out at \( T_{\text{rer}} = 30°C \).

HEAT INTEGRATION USING HEAT OF THE RESERVOIR

According to the technological regulations, some of the processes require the use of external energy (STEAM, CW20, CW5) for heating and cooling. The reduction of external energy used can be achieved by using a certain scheme of heat integration. The process of “Cooling” the reactor after sterilization does not coincide with the processes of preparation of the nutrient for sterilization in another reactor. For this reason, it is not possible to use the scheme of heat integration suggested in the publication by Boyadjiy et al. [4]. Therefore, heat reservoirs must be used to store the energy from the hot reactor, until it is utilized for the preparation of the nutrient in a subsequent reactor. It may also be used in the process of dilution after fermentation. A hot reactor is the fermenter \( F_H \) where the processes of feeding the raw materials and sterilization. (3.1-3.7). It should be cooled down to temperature of 30°C to carry out fermentation. A cold reactor (fermenter) \( F_C \), where the preparation of the nutrient and its sterilization is carried out.
According to the scheme suggested, the hot reactor $F_H$ is cooled with water CW20 using its serpentine. Thus, the water flowing out of the serpentine is stored in heat tank 1. It will subsequently be used when the processes of nutrient preparation are carried out in another fermentation reactor $F_C$ (processes 3.1-3.5). The volume of this heat tank should be as large as to
contain the amount of water necessary to maintain the processes. The second heat tank is designed to store the water required to carry out process 4.2, and its volume should be as large as the amount of water needed for the process. The design presented in Fig.1 can provide for the processes involved in the technological regulation. The task of process control is to determine the controlling variables ensuring minimum costs (water, vapor) the scheme.

**MATHEMATICAL MODEL**

It is assumed that for each of the four stages cooling will be carried out by certain dependence of the change of cooling water flow with time. This assumption provides a possibility to use models of the processes with ordinary differential equations. These equations describing the processes of heat- and mass transfer are:

1. An equation describing the change of the temperature of the mixture in reactor \( F_i \) when a flow of \( CW_20 \) or \( CW_5 \) of certain flow rate \( F_{W_i} \) is described by an equation for each time interval:

\[
\frac{dT_i}{dt} = \left( \Phi_i - \frac{1}{0} \right) \left( F_i C_{P_F} \right) \left( \frac{T_{i,in}^{\text{in}} - T_{i,in}}{T_{i,in}^{\text{in}} - T_{i,in}} \right) + \gamma_i \in \{1, 2\} (1)
\]

where:

- \( T_{i,in} = x_i T_{W,20} + (1 - x_i) T_{W,5} \), \( x_i = \{0 \text{ or } 1\} \),
- \( \Phi_i = \frac{F_i}{V_{G} C_{P,F}} \left( T_{i,in}^{\text{in}} - T_{i,in}^{\text{in}} \right) \) is the heat exchange surface of the serpentine in \( [m^2] \).
- \( U \) is the total coefficient of heat transfer, in \( [kWm^{-2}K^{-1}] \),
- \( C_F \), \( C_{P,20} \), \( C_{P,5} \) in \( [kJm^{-3}K^{-1}] \),
- \( C_{P,W} = x_i C_{P,20} + (1 - x_i) C_{P,5}, \) \( C_{P,20} \) and \( C_{P,5} \) are the specific heat capacities of \( CW_20 \) and \( CW_5 \),
- The flow rate of the cooling water through the serpentine is \( F_{W_i} [m^3/s] \).

2. The temperature at the serpentine outlet is determined for each time interval by the equation:

\[
T_{i} = \left( \Phi_i - \frac{1}{0} \right) T_{i,in} + \frac{1}{\Phi_i} T_{i,in} \gamma_i \in \{1 \text{ or } 2\} (2)
\]

The solution of equation (1) was to be found under initial condition \( T_{i,0} = T_{i,0}(0) \), at \( i = 1 \) and \( T_{i,0} = T_{i,0}(t+1) \) at \( i > 1 \). It should be taken into account that the temperature of the water flowing out of the serpentine \( T_{i,n} \) must be lower than that of the material contained in the fermenter \( T_{F_i} \) i.e. \( T_{F_i} \geq T_{i,n} \).

3. The volumes of the tanks \( S1, S2, SW \) and their temperatures for each time interval are described by:

\[
\begin{align*}
\frac{dV_{i}}{dt} &= \gamma_i S_i F_{W_i} \quad \gamma_i \in \{1, 2\} \\
C_{P,W} \frac{dT_{i}}{dt} &= \gamma_i S_i F_{W_i} (T_{i} - T_{i,n}) \\
\end{align*}
\]

At initial conditions \( V_{i,0}(0) = V_{i,0}(t+1) \), \( T_{i,n}(0) = T_{i,n}(t+1) \) and at \( i = 1 \) for the first time interval \( -1 \) \( V_{i,0}(0) = 0 \), \( T_{i,0}(0) = T_{i,n}(0) \).

At initial conditions \( V_{i,0}(0) = V_{i,0}(t+1) \), \( T_{i,0}(0) = T_{i,0}(t+1) \) and at \( i = 1 \) for the first time interval \( V_{i,0}(0) = 0 \), \( T_{i,0}(0) = T_{i,n}(0) \).

4. Cooling flow values \( F_{W_i}(t) \) with time. In general the flow through the cooling serpentine can be expressed by the expression:

\[
F_{W_i}(t) = \left\{ \begin{array}{ll}
\text{sign}(F_{MAX} - F_i(t)) + \\
\text{sign}(F_{MAX} - F_i(t)) F_{MAX} \\
\end{array} \right. \gamma_i \in \{1 \text{ or } 2\} (5)
\]

At \( F_i(t) = A_i + (B_i - A_i) \exp(-C_i t) \), \( i \in \{1 \text{ or } 2\} \).

Where \( \text{sign}(.) = 1 \) when \( (F_{MAX} - F_i(t)) \geq 0 \) and \( \text{sign}(.) = 0 \) at \( (F_{MAX} - F_i(t)) < 0 \).

The values of the coefficients \( A_i, B_i, C_i \) should be determined.

Another possible method for controlling the cooling water flow is at a constant flow rate within the intervals. This method is comparatively easy for implementation, but the effectiveness of each method should be compared. In this method the values of the coefficients are \( A_i = 0 \), \( B_i \geq 0 \) and \( C_i = 0 \) for each \( i \in \{1 \text{ or } 2\} \).
By the end of the fourth interval, when the procedure ends, the parameters of the heat tanks are $V_{S1}^*, V_{S2}^*, V_{SW}^*$ and $T_{S1}^*, T_{S2}^*, T_{SW}^*$.

**AIMS OF HEAT INTEGRATION**

The aim of heat integration is to minimize the quantities of resources used (vapor and cooling water) to accomplish the processes in both reactors. This can be achieved by providing maximum possible heat recovery from the cooled reactor. The heat stored in the tank $S1$ is further used for the preparation of the fermentation medium in another reactor, while the amount contained in $S2$ is used in stage 4.2. The energy used during the cooling with water $CW5$ should also be taken into account.

The objective function of heat integration is expressed by:

$$\text{Cost}_{\text{INT}} = \text{MIN}\{\text{Cost}_{\text{Steam}}^* + \text{Cost}_{WS}^* + \text{Cost}_{\text{Water}}^*\}. \quad (8)$$

where:
- $\text{Cost}_{\text{Steam}}^*$ is the cost of vapor,
- $\text{Cost}_{WS}^*$ is the cost of energy from $CW5$ by cooling,
- $\text{Cost}_{\text{Water}}^*$ is the cost of the water used to carry out the processes in the cases when heat reservoirs are used.

These components can be found using the following expressions:

$$\text{Cost}_{\text{Steam}}^* = C_{\text{Steam}}C_{W}V_{S1}^*\left(T_{S1}^* - T_{S1}\right) + C_{\text{Steam}}C_{W}V_{F}\left(T_{F} - V_{S1}^*\right) - T_{W20}\}, \quad (9)$$

$$\text{Cost}_{WS}^* = C_{WS}C_{W}V_{F}\left(T_{F3} - T_{F4}\right)\}, \quad (9)$$

$$\text{Cost}_{\text{Water}}^* = C_{W20}\left(V_{\text{Water}} - V_{S1}^*\right) + C_{W42}\left(V_{\text{Water}} - V_{S2}^*\right) + V_{SW}^*\right)\},$$

where,

$V_{\text{Water}} = V_{2,1} + V_{2,2} + V_{3,5}$,

$C_{WS}$ is the cost of unit energy from $CW5$ in lv/kJ,

$C_{\text{Steam}}$ is the cost of unit energy for vapor lv/kJ, while $C_{\text{Water}}$ - the cost of the water used lv/m$^3$.

**CONTROLLING VARIABLES**

The essence of the process control is to determine the controlling variables which would ensure that the minimum amount of resources is used in order to carry out the processes in the two reactors. These variables are:

$$\{A_i, B_i, C_i, t_i\}, \quad \forall i \in \overline{1,4} \quad (10)$$

as continuous variables defining the cooling water flow rate with time and the duration of each time interval, as well as

$$x_i = \{0, 1\}, \quad y_{i1} = \{0, 1\}, \quad y_{i2} = \{0, 1\}, \quad \forall i \in \overline{1,4} \quad (11)$$

as Boolean variables determining the sequence by which the cooling agents $CW5$ or $CW20$ are used.

IV. Constraints. The constraints are related to the requirements of the technology towards the duration of the processes and the technical limitations of the cooling devices (serpentine).

$$\sum_{i=1}^{4} t_i \leq t_f$$

$$V_{S1}^* \leq V_{2,1} + V_{2,2} + V_{3,5}$$

$$V_{S2}^* \leq V_{\text{Water}}$$

$$\sum_{i=1}^{4} \left(y_{i1}^* + y_{i2}^* + y_{i3}^*\right) \leq 1$$

$$\left(y_{i1}^* + y_{i2}^* + y_{i3}^*\right) = x_i, \forall i \in \overline{1,4}$$

$$\text{Cost}_{\text{INT}} < \text{Cost}_{\text{NO, INT}}$$

$$T_{F4} \leq T_{for}$$

where $\text{Cost}_{\text{NO, INT}}$ are the costs of energy and water, when the processes are carried out without heat integration.

**CONTROL WITH HEAT INTEGRATION**

For the control, the variables $(10)$ and $(11)$ should be determined. These variables should give a minimum of the goal function $(8)$ under the limitations posed by $(12)$.

The task formulated is that of MINLP, and it can also be solved using well known methods and programming systems such as GAMS Brooke A. D. et al. (1998) [5] or MATLAB [6].

**MOTIVATING EXAMPLE**

The suggested method of heat integration was implemented in a production line for antibiotics. The technological process consists of 6 main stages which have the following parameters (Antibiotics production of Actavista Co., Razgrad branch):

**Stage 1: Preparation of the nutrient**

1. This process is carried out by mixing micelles and the nutrient in a subsidiary reactor having a volume of $5m^3$. 

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**Stage 2: Preparation of the components of the fermentation medium**

1. Mixing $2m^3$ of component A with $V_{2.1} = 10m^3$, with water at $20^\circ C$ (CW 20), and stirring for 1 hour to obtain nutrient NMA.
2. Mixing $2m^3$ of component B with $V_{2.2} = 10m^3$, with CW 20, and stirring for 1 hour to obtain nutrient NMB.

**Stage 3: Process of fermentation**

1. Transfer of NMA to reactor $F_c$ and heating it from $20^\circ C$ to $55^\circ C$.
2. Heating NMA from $55^\circ C$ to $100^\circ C$ using water vapor.
3. Sterilization of NMA with water vapor at $100^\circ C$ for about 30 minutes.
4. Transfer NMB to $F_c$, and mixing it with NMA to obtain AB IAB.
5. Addition of $V_{3.5} = 17m^3$ to $18m^3$ and CW 20.
6. Heating the 42 m$^3$ mixture to $T = 55^\circ C$ with vapor to obtain the mixture NMAB.
7. Heating the mixture NMAB from $55^\circ C$ to $120^\circ C$ with water vapor for 1.5-2 hours.
8. Sterilization of NMAB with water vapor at $120^\circ C$ for 30 minutes.
9. Cooling NMAB from $120^\circ C$ to $45^\circ C$ using CW 20.
10. Cooling NMAB from $45^\circ C$ to $30^\circ C$ with $5^\circ C$ cooled water (CW 5) for 30 minutes.
11. Addition of IMX to NMAB for $t = 0.75h$ to volume of $47m^3$ to obtain FM.
12. Cooling the FM medium to $t = 30^\circ C$ using CW 5 and carry out fermentation for $120h-150h$ to obtain the product FB.

**Stage 4: Dilution**

1. Transfer FB to an intermediate reservoir for 1 hour.
2. Addition of $23m^3$ CW 20 for deactivation to obtain the product DFB.

**Stage 5: Filtration**

1. Filtration of DFB for $12h$ to obtain the concentrated material DSC.

**Stage 6: Sterilization of the empty fermenter**

1. Washing the empty fermenter with CW 20.
2. Sterilization of the washed fermenter with water vapor at $130^\circ C$ for 2h.

The process parameters are as follows:

\[ C_P = C_{P_{W_20}} = C_{P_{W_25}} = 4200kJm^{-3}K^{-1}, \]
\[ T_{W_5} = 5^\circ C, \]
\[ T_{W_20} = 20.00^\circ C, \]
\[ U = 1.20Kwm^{-2}K^{-1}, \]
\[ A = 56.55m^2, \]
\[ T_F(0) = T_w^* = T_F(0) = 120^\circ C, \]
\[ t_f = 6000s, \]
\[ V_{3.5} = 18m^3, \]
\[ F_{MAX} = 0.04m^3/s, \]
\[ V_{Waste} = 23m^3, \]
\[ V_{2.1} = V_{2.2} = 10m^3, \]
\[ C_{W_20} = 2.184LV/m^3, \]
\[ T_{fer} = 30^\circ C, \]
\[ C_{Steam} = (CG_{steam}/4.184)0^{-6} lv/kj, \]
\[ CG_{Steam} = 277.00lv/GCal, \]
\[ C_{W_5} = (CG_{W_5}/4.184)0^{-6} lv/kj, \]
\[ CG_{W_5} = 681.00lv/GCal. \]

The scheme of the heat integration of the processes was implemented, and the optimal controlling parameters were determined. MATLAB R2006a was used for the calculations and the optimization procedure was performed with the FMINCON module.

Table 1 shows the optimal values of the controlling parameters obtained from the solution of the optimization procedure according to the module used.

**Table 1. Continuous controlling variables**

<table>
<thead>
<tr>
<th>$i$</th>
<th>$t_{in}$ [sec]</th>
<th>$A_i$</th>
<th>$B_i$</th>
<th>$C_i$</th>
<th>$x_i$</th>
<th>$y_i^{S1}$</th>
<th>$y_i^{S2}$</th>
<th>$y_i^{SW}$</th>
<th>$T_{Stil}$ [°C]</th>
<th>$T_{F_i}(t_i)$ [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2005.8</td>
<td>0.0</td>
<td>0.0189</td>
<td>0.0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>64.75</td>
<td>79.50</td>
</tr>
<tr>
<td>2</td>
<td>601.9</td>
<td>0.0</td>
<td>0.0382</td>
<td>0.0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>64.75</td>
<td>69.26</td>
</tr>
<tr>
<td>3</td>
<td>1469.8</td>
<td>0.0</td>
<td>0.0400</td>
<td>0.0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>64.75</td>
<td>59.94</td>
</tr>
<tr>
<td>4</td>
<td>1922.5</td>
<td>0.0</td>
<td>0.0400</td>
<td>0.0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>64.75</td>
<td>30.00</td>
</tr>
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</table>

**Table 2. Discrete controlling variables**

<table>
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<tr>
<th>$i$</th>
<th>$t_{in}$ [sec]</th>
<th>$A_i$</th>
<th>$B_i$</th>
<th>$C_i$</th>
<th>$x_i$</th>
<th>$y_i^{S1}$</th>
<th>$y_i^{S2}$</th>
<th>$y_i^{SW}$</th>
<th>$T_{Stil}$ [°C]</th>
<th>$T_{F_i}(t_i)$ [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1784.8</td>
<td>0.0152</td>
<td>0.0219</td>
<td>1.0686e-4</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>62.2</td>
<td>81.8</td>
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<tr>
<td>2</td>
<td>575.7</td>
<td>0.0383</td>
<td>0.0400</td>
<td>1.0000e-4</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>62.2</td>
<td>71.5</td>
</tr>
<tr>
<td>3</td>
<td>1902.3</td>
<td>0.0400</td>
<td>0.0204</td>
<td>0.0100</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>62.2</td>
<td>48.3</td>
</tr>
<tr>
<td>4</td>
<td>1737.2</td>
<td>0.0400</td>
<td>0.0399</td>
<td>0.0100</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>62.2</td>
<td>30.0</td>
</tr>
</tbody>
</table>
Table 3. Costs of energy resources

<table>
<thead>
<tr>
<th>Resource</th>
<th>Costs for system without heat integration (I_W)</th>
<th>Costs for system with heat integration and continuous controlling variables (I_W)</th>
<th>Costs for system with heat integration and discrete controlling variables (I_W)</th>
<th>Saving %</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Cost_{\text{STEAM}})</td>
<td>1168.40</td>
<td>720.84</td>
<td>695.23</td>
<td>38.30(40.49)</td>
</tr>
<tr>
<td>(Cost_{W_{20}})</td>
<td>377.15</td>
<td>161.24</td>
<td>128.41</td>
<td>57.24(66.00)</td>
</tr>
<tr>
<td>(Cost_{W_{5}})</td>
<td>389.89</td>
<td>527.95</td>
<td>601.48</td>
<td>-35.40(-54)</td>
</tr>
<tr>
<td>(Cost_{\text{SUM}})</td>
<td>1935.44</td>
<td>1410.03</td>
<td>1425.12</td>
<td>27.14(26.36)</td>
</tr>
</tbody>
</table>

The controlling variables for the case when the cooling flows have flow rates constant in time but different in time intervals, i.e. the case of quasi-optimal control, are presented in Table 2.

Fig. 2 shows the change of the temperatures in the reactor and at the serpentine outlet during the time intervals for the case when heat integration was used with continuous controlling variables. Fig. 3 is for the case with discrete variables.

The costs of the resources used for heating and cooling in the system with two heat tanks under optimal control, as well as that for a system without heat integration, are presented in Table 3.

It can be seen that heat integration and optimal control of the process gives substantial reduction of water CW20 used for cooling by 57% and increase of cooling water CW5 by 35%. Simultaneously, the water vapor necessary for the processes decreases by about 38%. The use of heat tanks obviates the necessity to co-ordinate the processes in all reactors, and results in a total saving of energy sources (cooling water and water vapor) of about 27%. It should also be noted that the heat integration system decreased the consumption of water vapor and cooling water CW20.

The optimal control system requires a special device designed to follow the optimal law for controlling the cooling water flow rates (Fig. 4) in the individual intervals. A much simpler law for controlling the cooling water flow rates (Fig. 5) can be used by quasi-optimal control, and the economical results obtained would be similar. Furthermore, the quasi-optimal control does not require special controlling devices, thereby making its implementation much easier.
CONCLUSION

On the basis of the obtained results, the following can be concluded:

A new structure for heat integration with two heat storage tanks and an appropriate mathematical model are developed. An optimal process control strategy is proposed. The optimization task is formulated in terms of the Mixed Integral Non-Linear Programming (MINLP) with minimization of the cost of used resources.

The proposed method is successfully applied to the industrial process of antibiotics production.

NOTATIONS

\( F_H \)  
Hot reactor

\( F_C \)  
Cold reactor

\( S1 \)  
Heat tank 1

\( S2 \)  
Heat tank 2

\( SW \)  
Heat tank \( SW \) 2

\( NMA \)  
Mixture of water with component A

\( NMB \)  
Mixture of water with component B

\( AB_\_IAB \)  
Mixture of NMA and NMB

\( NMAB \)  
Nutrient medium

\( IMX \)  
Mixture of water and nutrients in the reactor auxiliary

\( FM \)  
Fermentation medium - mixture of \( IMX \) and \( NMAB \)

\( DFB \)  
The deactivated product after termination of fermentation

\( CW5 \)  
Water with 5\(^\circ\)C

\( CW20 \)  
Water with 20\(^\circ\)C

\( T_{Fi} \)  
Temperature of the hot fermenter during \( t \) - time interval\([\,^\circ\text{C}]\)

\( T_{W20} \)  
Temperature of the water \( CW20 \) \([\,^\circ\text{C}]\)

\( T_{W5} \)  
Temperature of the water \( CW5 \) \([\,^\circ\text{C}]\)
Temperature in the heat tank \( S1 \) during \( i \)-time interval \([\,^{\circ}C]\) \\
Temperature in the heat tank \( S2 \) during \( i \)-h time interval \([\,^{\circ}C]\) \\
The temperature in the heat tank \( SW \) during \( i \)-time interval, \([\,^{\circ}C]\) \\
Water temperature at the entrance of the coil \([\,^{\circ}C]\) \\
Water temperature at the output of the coil \([\,^{\circ}C]\) \\
Volume of the hot fermenter \([m^3]\) \\
Volume of water in the heat tank \( S1 \) during \( i \)-time interval \([m^3]\) \\
Volume of water in the heat tank \( S2 \) during \( i \)-time interval \([m^3]\) \\
Volume of water in the heat tank \( SW \) during \( i \)-time interval \([m^3]\) \\
Volume of water in the heat tank \( S1 \) in the end of the \( i \)-time interval \([m^3]\) \\
Volume of water in the heat tank \( S2 \) in the end of the \( i \)-time interval \([m^3]\) \\
Volume of water in the heat tank \( SW \) in the end of the \( i \)-time interval \([m^3]\) \\
Total volume of water used for the whole process \([m^3]\) \\
Volume of \( NMA \) during stage 2.1 \([m^3]\) \\
Volume of \( NMB \) during stage 2.1 \([m^3]\) \\
Volume of water added in stage 3.5 \([m^3]\) \\
Specific heat capacities of hot fermenter \([kJm^3K^{-1}]\) \\
Specific heat capacities of water \( CW20 \) \([kJm^3K^{-1}]\) \\
Specific heat capacities of water \( CW5 \) \([kJm^3K^{-1}]\) \\
Specific heat capacities of used water \([kJm^3K^{-1}]\) \\
Binary variable \( y_{i1}^{S1} = \{0 \lor 1\} \) \\
Binary variable \( y_{i2}^{S2} = \{0 \lor 1\} \) \\
Binary variable \( y_{i}^{SW} = \{0 \lor 1\} \) \\
Binary variable \( x_{i} = \{0 \lor 1\} \) \\
Flow rate of the cooling water through the coil \([m^3/s]\) \\
Heat transfer surface of the coil \([m^2]\) \\
Overall heat transfer coefficient \([kWm^{-2}K^{-1}]\) \\
Values of the coefficients should be determined \\

Value of steam used for process \([l.v]\) \\
Value of the energy use of cooling water \( CW5 \) \([l.v]\) \\
Value the water used to carry out the processes in the cases when heat reservoirs are used \([l.v]\) \\
Price per unit of energy used for process steam \([l.v/kJ]\) \\
Price per unit of energy used for cooling water \( CW5 \) process \([l.v/kJ]\) \\
Price per unit volume of cooling water \( CW20 \) used for process \([l.v./m^3]\) \\
Cost of energy and water required to the process in the case in absence of heat integration \([l.v]\) \\
Price per unit of energy used for process steam \([l.v/GCal]\)
Price per unit of energy used for process cooling water $CG_{W^5}$ \( [\text{$/GCal}]\)

Price per unit of energy used for process cooling water $CW_{W^5}$ \( [\text{$/kJ}]\)

Duration of the i-time interval \( [s] \)

Time to complete the cooling process \( [s] \)

Bulgarian Leva

**REFERENCES**


**ОПТИМАЛНО УПРАВЛЕНИЕ ПОТРЕБЛЕНИЕТО НА ЕНЕРГИЯТА ПРИ ПРОИЗВОДСТВОТО НА АНТИБИОТИКИ**

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(Резюме)

Енергийната ефективност е много важен показател при оценката на стабилността на промишлените процеси. Оптималното използване на енергията е основна задача и днес, тъй като тя определя състоянието на околната среда, технологиите и цената на продукта. В настоящата работа се описва метод за намаляване потреблението на енергия в резултат на топлина интеграция в система биореактори за производство на антибиотици. Предложена е схема за топлинната интеграция с два топлинни резервоара. Разработен е математичен модел на процесите, които протичат в двата реактора. Използваните този модел е предложен метод за управление на енергийните ресурси, чрез топлинна интеграция с два топлинни резервоара. Задачата за управление е формулирана като задача на смесеното нелинейно програмиране. Методът е тестван на примера на производството на антибиотици.