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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.

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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 20ºC (*CW*20) by stirring for 1 hour until nutrition medium *NMA* is obtained.
2. Mixing of component V_1 from Tank *B* with V_{22} *CW*20 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 20ºC to 55ºC.
2. Heating *NMA* from 55° to 100°C using steam.
3. Sterilization of *NMA* with 100°C steam for about 0.5 h.
4. Transfer of *NMB* to F_C and mixing it with *NMA* to obtain *AB_IAB*.
5. Addition of V_{35} *CW*20.
6. Heat the mixture V_C with vapor to T = 55ºC to obtain medium *NMAB*.
7. Heat the mixture *NMAB* with water vapor from 55ºC to 120ºC.
8. Sterilization of *NMAB* with water vapour at temperature of 120ºC.
9. Cooling *NMAB* from 120ºC to 45ºC using *CW*20.
10. Cooling of *NMAB* from 45ºC to 30ºC using 5ºC cooled water (*CW5*).
11. Addition of *IMX* to *NMAB* up to volume V_{max} to obtain *FM*.
12. Cooling the medium *FM* to T_{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 *CW*20 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 *CW*20.
2. Sterilization of the washed fermenter with water vapor with temperature of 130ºC.
3. Sterilization of the washed fermenter with water vapor with temperature of 130ºC.

PROCESS ORGANIZATION

According to the technology (Stages 1-6), there are a number of processes requiring the use of external energy (*STEAM*, *CW*20, *CW*5) 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_{str} = 120ºC. Processes 3.8 and 3.9 are carried out at T_{str} = 30ºC.

HEAT INTEGRATION USING HEAT OF THE RESERVOIR

According to the technological regulations, some of the processes require the use of external energy (*STEAM*, *CW*20, *CW*5) 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 Boyadjiev *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 30ºC to carry out fermentation. A cold reactor (fermenter) F_C , where the preparation of the nutrient and its sterilization is carried out.

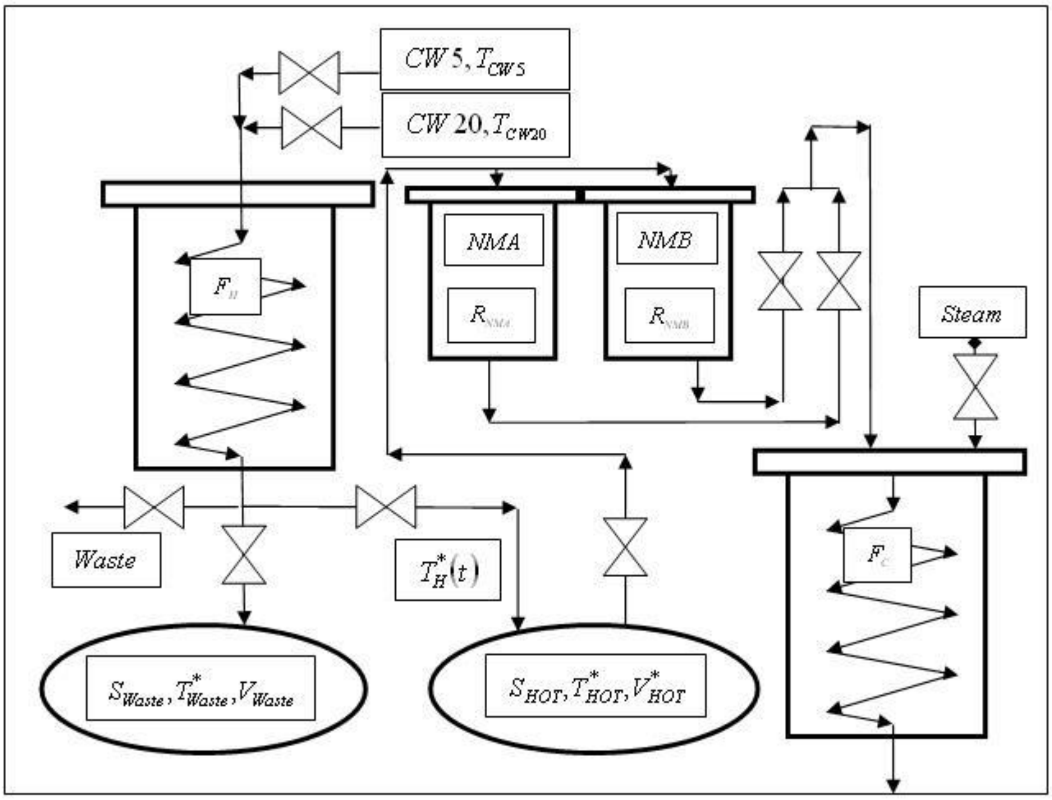

Fig 1a. Heat integration with heat reservoirs.

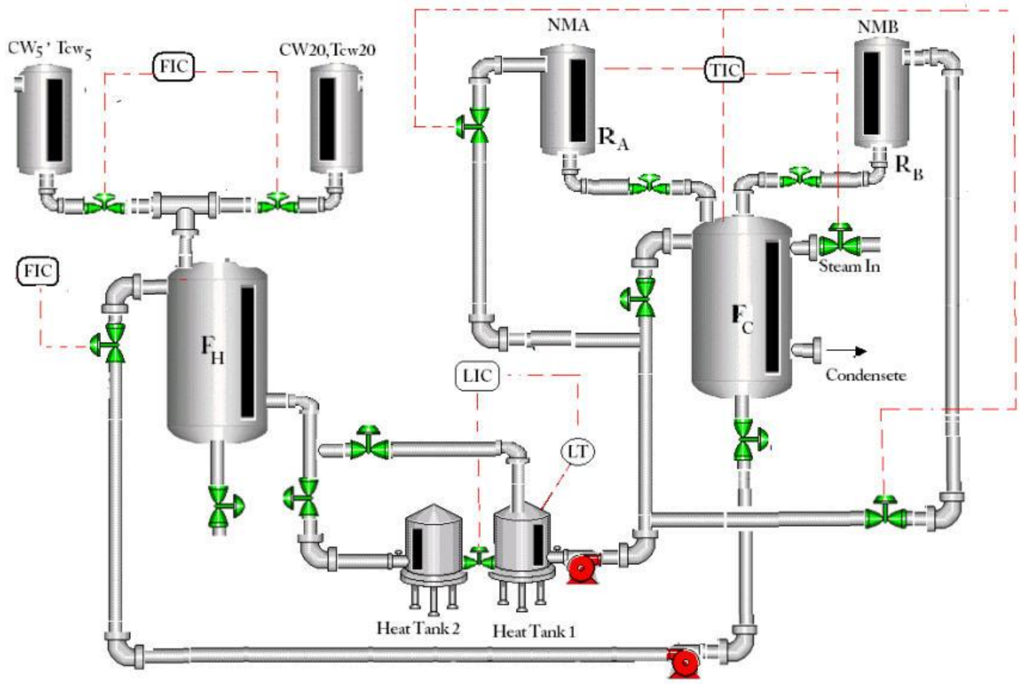

Fig 1b. Piping and instrumentation diagram for heat integration and heat reservoirs.

According to the scheme suggested, the hot reactor F_H is cooled with water *CW*20 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_H when a flow of $CW20$ or $CW5$ of certain flow rate F_{Wi} - is described by an equation for each time interval:

$$\frac{dT_{Fi}}{dt} = \frac{(\Phi_{Wi}-1)}{\Phi_{Wi}} \frac{(F_{Wi}Cp_{Wi})}{V_F Cp_F}\left(T_i^{in} - T_{Fi}\right), \forall i \in (1 \div 4) \quad (1)$$

where:

- $T_i^{in} = x_i T_{W20} + (1-x_i) T_{W5}$, $x_i = \{0 \vee 1\}$,
- $\Phi_{Wi} = \left|\frac{T_{Fi} - T_i^{in}}{T_{Fi} - T_i^*}\right| = \exp\left(\frac{UA}{F_{Wi}Cp_{Wi}}\right)$, A is the heat exchange surface of the serpentine in $\left[m^2\right]$,
- U is the total coefficient of heat transfer, in $\left[kWm^{-2}K^{-1}\right]$,
- Cp_F, Cp_{W20}, Cp_{W5} in $\left[kJm^{-3}K^{-1}\right]$,
- $Cp_{Wi} = x_i Cp_{W20} + (1-x_i) Cp_{W5}$, Cp_{W20} and C_{pw5} are the specific heat capacities of $CW20$ and $CW5$.
- The flow rate of the cooling water through the serpentine is F_{wi} [m^3/s].

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

$$T_i^* = \frac{(\Phi_{Wi}-1)}{\Phi_{Wi}} T_{Fi} + \frac{1}{\Phi_{Wi}} T_i^{in}, \quad \forall i \in (1 \div 4) \quad (2)$$

The solution of equation (1) was to be found under initial condition $T_{Fr}(0)$, where $T_{Fr}(0) = T_{str}(0)$, at $i=1$ and $T_{Fr}(0) = T_{Fri}(0)(t_{i-1})$ at $i>1$. It should be taken into account that the temperature of the water flowing out of the serpentine T_i^* must be lower than that of the material contained in the fermenter T_{Fri} i.e. $T_{Fi} \geq T_i^*$.

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

$$\left.\begin{aligned} \frac{dV_{S1}^i}{dt} &= y_i^{S1} F_{Wi} \\ Cp_{Wi} V_{S1}^i \frac{dT_{S1}^i}{dt} &= y_i^{S1} F_{Wi} Cp_{Wi}\left(T_i^* - T_{S1}^i\right) \end{aligned}\right\}, \forall i \in (1 \div 4) \quad (3)$$

At initial conditions $V_{S1}^i(0) = V_{S1}^{(i-1)}\left(t_{(i-1)}\right)$, $T_{S1}^i(0) = T_{S1}^{(i-1)}\left(t_{(i-1)}\right)$ and at $i=1$ for the first time interval – 1 $V_{S1}^i(0) = 0$, $T_{S1}^i(0) = T_i^{in}$.

$$\left.\begin{aligned} \frac{dV_{S2}^i}{dt} &= y_i^{S2} F_{Wi} \\ Cp_{Wi} V_{S2}^i \frac{dT_{S2}^i}{dt} &= y_i^{S2} F_{Wi} Cp_{Wi}\left(T_i^* - T_{S2}^i\right) \end{aligned}\right\}, \forall i \in (1 \div 4) \quad (4)$$

At initial conditions $V_{S2}^i(0) = V_{S2}^{(i-1)}\left(t_{(i-1)}\right)$, $T_{S2}^i(0) = T_{S2}^{(i-1)}\left(t_{(i-1)}\right)$ and at $i=1$ for the first time interval – $V_{S1}^i(0) = 0$, $T_{S2}^i(0) = T_i^{in}$.

$$\left.\begin{aligned} \frac{dV_{SW}^i}{dt} &= y_i^{SW} F_{Wi} \\ Cp_{Wi} V_{SW}^i \frac{dT_{SW}^i}{dt} &= y_i^{SW} F_{Wi} Cp_{Wi}\left(T_i^* - T_{SW}^i\right) \end{aligned}\right\}, \forall i \in (1 \div 4) \quad (5)$$

At initial conditions $V_{SW}^i(0) = V_{SW}^{(i-1)}\left(t_{(i-1)}\right)$, $T_{SW}^i(0) = T_{SW}^{(i-1)}\left(t_{(i-1)}\right)$ and at $i=1$ for the first time interval $-V_{SW}^i(0) = 0$, $T_{SW}^i(0) = T_i^{in}$, $y_i^{S1} = \{0 \vee 1\}$, $y_i^{S2} = \{0 \vee 1\}$, $y_i^{SW} = \{0 \vee 1\}$ depending on the that whether the corresponding heat tank is filled during the given time interval or not.

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

$$F_{Wi}(t) = \left.\begin{aligned} &sign\left(F_{MAX} - F_i(t)\right) + \\ &\left(1 - sign\left(F_{MAX} - F_i(t)\right)\right) F_{MAX} \end{aligned}\right\}, \forall i \in (1 \div 4), \quad (6)$$

at

$$F(t)_i = A_i + (B_i - A_i)\exp(-C_i t), \quad \forall i \in (1 \div 4), \quad (7)$$

Where $sign(.) = 1$ when $\left(F_{MAX} - F_i(t)\right) \geq 0$ and $sign(.) = 0$ at $\left(F_{MAX} - F_i(t)\right) < 0$. 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 $i \in (1 \div 4)$.

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:

$$Cost_{INT} = MIN\left\{Cost_{Steam}^* + Cost_{W5}^* + Cost_{Water}^*\right\}, \quad (8)$$

where:

- $Cost_{Steam}^*$ is the cost of vapor,
- $Cost_{W5}^*$ is the cost of energy from $CW5$ by cooling,
- $Cost_{Water}^*$ 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:

$$\left.\begin{aligned} Cost_{Steam}^* &= C_{Steam}Cp_W V_{S1}^*\left(T_{St}^* - T_{S1}^*\right) + \\ &\quad C_{Steam}Cp_W\left(V_F - V_{S1}^*\right)\left(T_{St}^* - T_{W20}\right), \\ Cost_{W5}^* &= C_{W5}Cp_F V_F\left(T_{F3} - T_{F4}\right), \\ Cost_{Water}^* &= C_{W20}\begin{pmatrix}\left(V_{Water} - V_{S1}^*\right) + \\ \left(V_{4.2.} - V_{S2}^*\right) + V_{SW}^*\end{pmatrix} \end{aligned}\right\}, (9)$$

where,

$$V_{Water} = V_{2.1.} + V_{2.2.} + V_{3.5.},$$

C_{W5} is the cost of unit energy from $CW5$ in lv/kJ,
C_{Steam} is the cost of unit energy for water vapor lv/kJ, while C_{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:

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

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

$$\left.\begin{aligned} x_i = \{0 \vee 1\},\ y_i^{S1} = \{0 \vee 1\}, \\ y_i^{S2} = \{0 \vee 1\},\ y_i^{SW} = \{0 \vee 1\} \end{aligned}\right\}, \quad \forall i \in \overline{1,4} \quad (11)$$

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).

$$\left.\begin{aligned} &\sum_{i=1}^{i=4} t_i \le t_f \\ &V_{S1}^* \le V_{2.1} + V_{2.2} + V_{3.5} \\ &V_{S2}^* \le V_{Waste} \\ &\sum\left(y_i^{S1} + y_i^{S2} + y_i^{SW}\right) \le 1 \\ &\left(y_i^{S1} + y_i^{S2} + y_i^{SW}\right) = x_i, \forall i \in \overline{1,4} \\ &Cost_{INT} < Cost_{NO\_INT} \\ &T_{F4} \le T_{fer} \end{aligned}\right\}, (12)$$

where $Cost_{NO\_INT}$ 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 $5m^3$.

***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^oC ($CW20$), and stirring for 1 hour to obtain nutrient NMA.
2. Mixing $2m^3$ of component B with $V_{2.2.} = 10m^3$, with $CW20$, 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^oC to 55^oC.
2. Heating NMA from 55^oC to 100^oC using water vapor.
3. Sterilization of NMA with water vapor at 100^oC 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 $CW20$.
6. Heating the 42 m^3 mixture to $T = 55^oC$ with vapor to obtain the mixture $NMAB$.
7. Heating the mixture $NMAB$ from 55^oC to 120^oC with water vapor for 1.5-2 hours.
8. Sterilization of $NMAB$ with water vapor at 120^oC for 30 minutes.
9. Cooling $NMAB$ from 120^oC to 45^oC using $CW20$.
10. Cooling $NMAB$ from 45^oC to 30^oC with 5^oC cooled water ($CW5$) 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 $t = 30^oC$ using $CW5$ 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 $23m^3$ $CW20$ 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 $CW20$.
2. Sterilization of the washed fermenter with water vapor at 130^oC for $2h$.

The process parameters are as follows:
$Cp_F = Cp_{W20} = Cp_{W5} = 4200\,kJm^{-3}K^{-1}$, $T_{W5} = 5^oC$,
$T_{W20} = 20.00^oC$, $U = 1.20kWm^{-2}K^{-1}$,
$A = 56.55m^2$, $T_F(0) = T_{st}^* = T_{F0} = 120^oC$,
$t_f = 6000s$, $V_{3.5.} = 18m^3$, $F_{MAX} = 0.04m^3/s$,
$V_{Waste} = 23m^3$, $V_{2.1.} = V_{2.2.} = 10m^3$,
$C_{W20} = 2.184lv/m^3$, $T_{fer} = 30^oC$,
$C_{Steam} = (CG_{steam}/4.184)10^{-6}\ lv/kJ$,
$CG_{Steamt} = 277.00lv/GCal$,
$C_{W5} = (CG_{W5}/4.184)10^{-6}\ lv/kJ$,
$CG_{W5} = 681.00lv/GCal$.

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

i	t_{in} [sec.]	A_i	B_i	C_i	x_i	y_i^{S1}	y_i^{S2}	y_i^{SW}	$T_{St1}\ ^oC$	$T_{Fi}(t_i)\ ^oC$
1	2005.8	0.0	0.0189	0.0	1	1	0	0	64.75	79.50
2	601.9	0.0	0.0382	0.0	1	0	1	0	64.75	69.26
3	1469.8	0.0	0.0400	0.0	1	0	0	1	64.75	50.94
4	1922.5	0.0	0.0400	0.0	0	0	0	0	64.75	30.00

Table 2 Discrete controlling variables

i	t_{in} [sec.]	A_i	B_i	C_i	x_i	y_i^{S1}	y_i^{S2}	y_i^{SW}	$T_{St1}\ ^oC$	$T_{Fi}(t_i)\ ^oC$
1	1784.8	0.0152	0.0219	1.0686e-4	1	1	0	0	62.2	81.8
2	575.7	0.0383	0.0400	1.0000e-4	1	0	1	0	62.2	71.5
3	1902.3	0.0400	0.0204	0.0100	1	0	0	1	62.2	48.3
4	1737.2	0.0400	0.0399	0.0100	0	0	0	0	62.2	30.0

Table 3. Costs of energy resources

Resource	Costs for system without heat integration *lw.*	Costs for system with heat integration and continuous controlling variables *lw.*	Costs for system with heat integration and discrete controlling variables *lw.*	Saving %
$Cost_{STEAM}$	1168.40	720.84	695.23	38.30(40.49)
$Cost_{W20}$	377.15	161.24	128.41	57.24(66.00)
$Cost_{W5}$	389.89	527.95	601.48	-35.40(-54)
$Cost_{SUM}$	**1935.44**	**1410.03**	**1425.12**	**27.14(26.36)**

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.

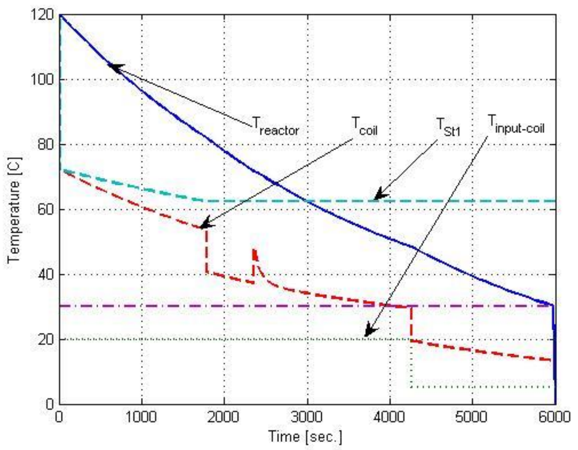

Fig. 2. Change of the temperatures in the reactor for the case of the system with heat integration and continuous controlling variables.

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.

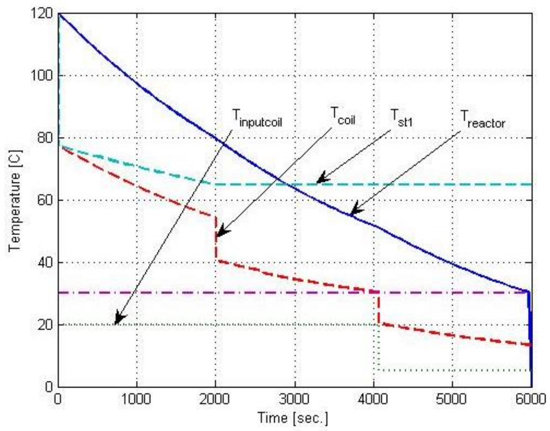

Fig.3. Change of the temperatures in the reactor for the case of the system with heat integration and discrete controlling variables.

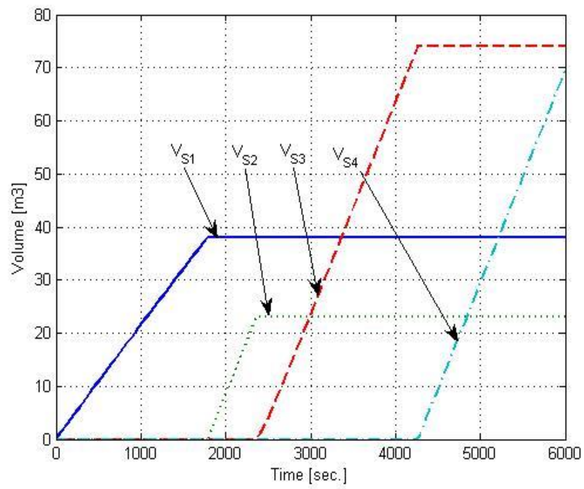

Fig.4. Change of heat tank volumes with time under continuous controlling variables .

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.

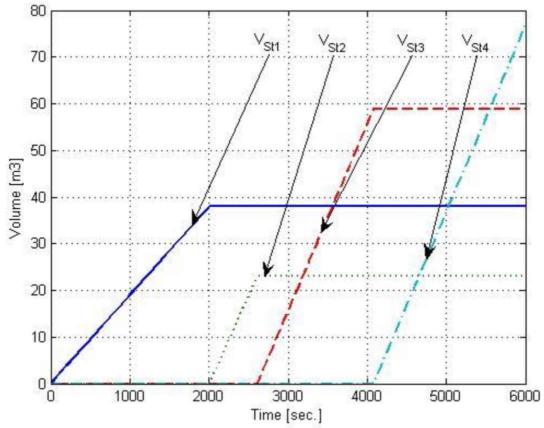

Fig.5. Change of heat tank volumes with time under discrete controlling variables.

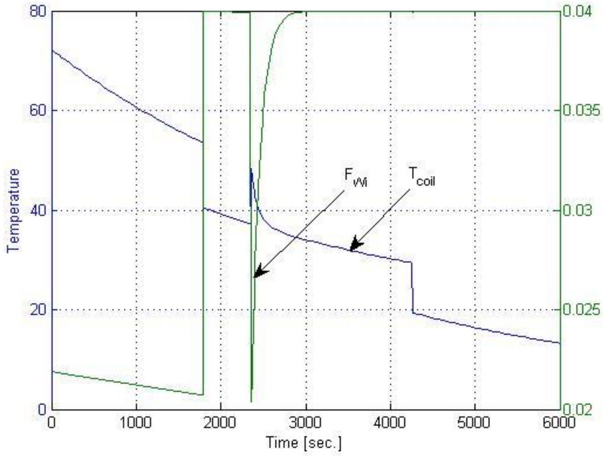

Fig. 6. Change of cooling agents flow rates under continuous controlling variables.

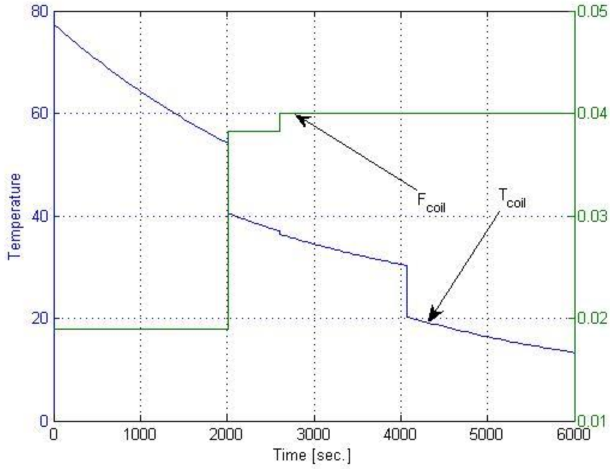

Fig. 7. Change of cooling agents flow rates under discrete controlling variables.

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^oC
$CW20$	Water with 20^oC
T_{Fi}	Temperature of the hot fermenter during t - time interval $\left[{}^oC\right]$
T_{W20}	Temperature of the water $CW20$ $\left[{}^oC\right]$
T_{W5}	Temperature of the water $CW5$ $\left[{}^oC\right]$

T_{S1}^{i}	Temperature in the heat tank $S1$ during i- time interval $\left[{}^{o}C\right]$
T_{S2}^{i}	The temperature in the heat tank $S2$ during i-h time interval $\left[{}^{o}C\right]$
T_{SW}^{i}	The temperature in the heat tank SW during i- time interval, $\left[{}^{o}C\right]$
T_{i}^{in}	Water temperature at the entrance of the coil $\left[{}^{o}C\right]$
T_{i}^{*}	Water temperature at the output of the coil $\left[{}^{o}C\right]$
V_{F}	Volume of the hot fermenter $\left[m^{3}\right]$
V_{S1}^{i}	Volume of water in the heat tank $S1$ during i- time interval $\left[m^{3}\right]$
V_{S2}^{i}	Volume of water in the heat tank $S2$ during i- time interval $\left[m^{3}\right]$
V_{SW}^{i}	Volume of water in the heat tank SW during i- time interval $\left[m^{3}\right]$
V_{S1}^{*}	Volume of water in the heat tank $S1$ in the end of the i- time interval $\left[m^{3}\right]$
V_{S2}^{*}	Volume of water in the heat tank $S2$ in the end of the i- time interval $\left[m^{3}\right]$
V_{SW}^{*}	Volume of water in the heat tank SW in the end of the i time interval $\left[m^{3}\right]$
V_{Water}	Total volume of water used for the whole process $\left[m^{3}\right]$
$V_{2.1.}$	Volume of NMA during stage 2.1 $\left[m^{3}\right]$
$V_{2.2.}$	Volume of NMB during stage 2.1 $\left[m^{3}\right]$
$V_{3.5.}$	Volume of water added in stage 3.5 $\left[m^{3}\right]$
Cp_{F}	Specific heat capacities of hot fermenter $\left[kJm^{-3}K^{-1}\right]$
Cp_{W20}	Specific heat capacities of water $CW20$ $\left[kJm^{-3}K^{-1}\right]$
Cp_{W5}	Specific heat capacities of water $CW5$ $\left[kJm^{-3}K^{-1}\right]$
Cp_{Wi}	Specific heat capacities of used water $\left[kJm^{-3}K^{-1}\right]$
y_{i}^{S1}	Binary variable $y_{i}^{S1}=\{0\vee 1\}$
y_{i}^{S2}	Binary variable $y_{i}^{S2}=\{0\vee 1\}$
y_{i}^{SW}	Binary variable $y_{i}^{SW}=\{0\vee 1\}$
x_{i}	Binary variable $x_{i}=\{0\vee 1\}$
F_{Wi}	Flow rate of the cooling water through the coil $\left[m^{3}/s\right]$.
A	Heat transfer surface of the coil $\left[m^{2}\right]$
U	Overall heat transfer coefficient $\left[kWm^{-2}K^{-1}\right]$,
$\left.\begin{matrix}A_{i}\\B_{i}\\C_{i}\end{matrix}\right\}$	Values of the coefficients should be determined
$Cost_{Steam}^{*}$	Value of steam used for process $\left[lv\right]$
$Cost_{W5}^{*}$	Value of the energy use of cooling water $CW5$ $\left[lv\right]$
$Cost_{Water}^{*}$	Value the water used to carry out the processes in the cases when heat reservoirs are used $\left[lv\right]$
C_{Steam}	Price per unit of energy used for process steam $\left[lv/kJ\right]$
C_{W5}	Price per unit of energy used for cooling water $CW5$ process $\left[lv/kJ\right]$
C_{Water}	Price per unit volume of cooling water $CW20$ used for process $\left[lv./m^{3}\right]$
$Cost_{NO\_INT}$	Cost of energy and water required to the process in the case in absence of heat integration $\left[lv\right]$
CG_{Steamt}	Price per unit of energy used for process steam $\left[lv/GCal\right]$

CG_{W5}	Price per unit of energy used for process cooling water $CW5$ $[lv/GCal]$
C_{W5}	Price per unit of energy used for process cooling water $CW5$ $[lv/kJ]$
t_i	Duration of the i-time interval $[s]$
t_f	Time to complete the cooling process $[s]$
lv	Bulgarian Leva

REFERENCES

1 Vaselenak J. A., Grossmann I. E., Westerberg A. W., Heat integration in batch processing, *Ind. Eng. Chem. Process Des. Dev*., Vol. 25, No. 2, pp. 357-366, 1986.

2 Ivanov B., Peneva K., Vaklieva-Bancheva N., Synthesis of Cost Optimal Heat Integrated Batch Systems, *Hung. J. Ind. Chem*., Vol. 21, pp. 7-14, 1993.

3 Ivanov B., Vaklieva-Bancheva N., Peneva K., Synthesis of Batch Systems with Heat Storage Tanks. Design and Retrofit Problems, *Bulg. Chem. Com*., Vol. 26, No 1, pp. 122-133, 1993. Boyadjiev Ch., Ivanov B., Vaklieva-Bancheva N., Pandelides C., Shah N., Optimal energy integration in batch antibiotics manufacture, *Comp. Chem. Eng*., Vol. 20, S31-S36, 1996.

4 Brooke A., Kendrick D., Meeraus A., Raman R., GAMS: A User's Guide, GAMS Development Corporation, Washington, 1998.

5 User’s Guide: Optimization Toolbox For Use with MATLAB_, Version 5, 2006, USA, The MathWorks, Inc. http://www.mathworks.com.

ОПТИМАЛНО УПРАВЛЕНИЕ ПОТРЕБЛЕНИЕТО НА ЕНЕРГИЯТА ПРИ ПРОИЗВОДСТВОТО НА АНТИБИОТИЦИ

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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. Използвайки 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.