

**IMPROVING THE ENERGY EFFICIENCY OF INDUSTRIAL BATCH
PROCESS USING HEAT INTEGRATION**

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Abstract

Energy efficiency has become a very important term for evaluating the sustainability of industrial processes. Due to environmental, but also economical reasons, the readiness for optimizing a process is gaining ground. In this study the problem of reduction of energy consumption in bioreactors system of antibiotics production by means of energy integration is considered. An energy integration scheme is proposed, which provides both to the process of cooling a reactor after its sterilization and preparation of Substrate to another reactor. A mathematical model of processes in both reactors is developed. By using this model a method for managing the processes of heat integration is created. The problem is formulated in the terms of MINLP. The efficiency of proposed approach is illustrated on the example of the industry.

Key words: Heat integration, Batch reactors, Optimal control, Quasioptimal control

1. INTRODUCTION

The reduction of greenhouse gas emissions and the question of how we will deal with our future energy demand, or increasing energy costs respectively, are important political and social issues nowadays. Enhancing energy efficiency and reducing energy use is therefore politically strengthened, e.g. by the EU directive 2006/ 32/ EG. One contribution to reduce the overall energy consumption would be to improve the energy efficiency of industrial processes, since many of them are based on high energy inputs. Besides the ecological aspects, this is of economical interest as well. Energy costs become more and more a matter of cost effectiveness for production processes. Concerning industrial processes, there are two major aspects controlling the energy demand which are primarily the state of the insulation-system, and secondly the process control. The problem of the value reduction for "Heating-Cooling" processes in batch reactors is topical, having in mind the changed economic conditions. This refers mostly to the pharmaceutical and food industry, which is characterized by multiple proceedings often using periodic reactors to perform basic operations. Reduction of energy consumption of such proceedings can be attained by creating conditions for optimal use of the internal energy in the system that is provided through heat integration of processes. One of the first studies to deal with these problems was *Vaselenak, et al. (1986)[1]*. Subsequently, *B. Ivanov, N. Vakiieva-Bantcheva (1994)[2]* and later further developed by *A. Pozna et al. (1998)[3]* dealt with power reactors in operation, proposing methods of heat-integrated systems synthesis. *T. Pinto et al. (2003)[4]* discusses the problem of energy saving by design of multipurpose systems or renovation of reexisting/ existing systems. Interesting mathematical models for modeling of the processes of energy consumption are proposed by *Patric s. et al. (2004) [5]*. Later *Majozi t. (2006)[6]* examines the

problem of energy saving in the operation of multipurpose systems, such as the task of synthesis as well as in systems with continuous processes. In the literature mainly are discussed the problems of analysis, modeling and synthesis of heat exchanger networks in the operation of multipurpose systems. There are few development in which apply theoretical methods in real manufacturing systems.

2. AIM

The aim of this study is to create a method for reducing energy consumption through heat integration of processes and their optimal management of a class periodic bioreactors for the production of antibiotics.

3. PROBLEM DESCRIPTION

Let consider a generalized superstructure bioreactors system for carry out of the substrate preparation process, sterilization and cooling till operational temperature of the fermentation process. The characteristic of the proposed scheme of organization of processes is that processes, cooling of the reactor after sterilization and the preparation of the substrate in next bioreactor are integrated by creating appropriate production plan and use of the cooling water for the purpose of the processes. This leads to reduction of the quantity waste water and use steam for process heating and sterilization. On Figure 1 is shown such type of scheme for the processes carrying out. The task of determining control action is limited to that the parameters of time intervals to be found, as well as the conditions for processes carrying out witch ensure a minimum price of used energy from external systems.

3.1. Process description

Antibiotic production involves processing tasks which realize in the batch reactors. According to technical regulation they have following sequence and parameters:

Step 1: Substrate preparation.

1. This processing task carries out through water and substrate mixing in an auxiliary reactor with volume of $5m^3$.

Step 2: Preparation of the components of the fermentation medium.

1. Mixing of $V_A = 2m^3$ component of A with $V_{2.1.} = 10m^3$ of water at $20^\circ C$ (CW20) through stirring until production of substrate NMA with volume of $V_{2.1.}^* = (V_{2.1.} + V_A)$.
2. Mixing of $V_B = 2m^3$ component of B with $V_{2.2.} = 10m^3$ of water CW20 by stirring until substrate NMB with volume of $V_{2.2.}^* = (V_{2.2.} + V_B)$ is produced/generated.

Step 3: Fermentation process.

1. Simultaneous transfer of NMA in the fermentation reactor and its heating by means of steam from temperature $T_{3.2.} = 20^\circ C$ to temperature $T_{3.2.} = 55^\circ C$.
2. Heating of NMA by steam from $T_{3.2.} = 55^\circ C$ to $T_{3.2.} = 100^\circ C$.
3. Steam sterilization of NMA at $T_{st} = 100^\circ C$ approximately within 0.5 hours.

4. NMB transfer into the fermentation reactor and mixing with NMA to produce substrate *AB IAB*.
5. Adding of $V_{3.5} = 17m^3 \div 18m^3$ of technical water *CW20* with temperature $20^\circ C$ in order to produce substrate *NMAB*.
6. Steam heating of $42m^3$ NMAB until temperature of $T_{3.6} = 55^\circ C$.
7. Steam heating of NMAB from $T_{3.6} = 55^\circ C$ to $T_{3.6} = T_{St}^* = 120^\circ C$ approximately within 2 hours.
8. Sterilization of NMAB by steam $T_{St}^* = 120^\circ C$ approximately within 0.5 hours.
9. Cooling of NMAB with water *CW20* from $T_{3.9} = T_{St}^* = 120^\circ C$ until $T_{3.9} = 45^\circ C$.
10. Cooling of NMAB with $T_5 = 5^\circ C$ water *CW5* from $T_{3.10} = 45^\circ C$ until $T_{3.10} = T_{Work} = 30^\circ C$ approximately within 0.5 hours.
11. Adding of *IMX* to *NMAB* within 0.75 hours to reach the volume of $47m^3$ which represents the substrate *FM*.
12. Fermentations substrate cools until $T_{Work} = 30^\circ C$ by using *CW5* and the fermentation process continues in the same temperature within 120-150 hours until fermentation product FB is formed.

Step 4: Dilution

1. Transfer of FB to an intermediate tank approximately within 1 hour.
2. Adding of $V_{Waste} = 23m^3$ of water *CW20* and deactivation approximately within 1 hour to obtain fermentation product DFB.

Step 5: Filtration

1. Filtration of the diluted product DFB approximately within 12 hours until concentrated raw material DSC is produced.

Step 6: Sterilization of the empty fermenter reactor.

1. Rinsing of the empty fermenter reactor by using water *CW20*.
2. Sterilization of the reactor using steam at $130^\circ C$ approximately within 2 hours.

3.2. Description of the processes equipment

The process is carried out in an industrial unit having the following equipment: which involves the following equipment:

1. 8 (preparatory) reactors (with volume) of $5 / 8m^3$ for the processes 1.1
2. 3 reactors for substrate with volume of $12 / 16m^3$ for processes 2.1 and 2.2
3. 14 fermentation reactors with volume of $47 / 63m^3$ for processes 3.1 to 3.11 and 6.1, 6.2.

They are equipped with 3 coil heat exchangers each of them with length of $100m$, diameter of $57mm$ and thickness of wall of, $3.5mm$.

4. 3 tanks with volume $70/100m^3$ for the processes 4.1 and 4.2.
5. 3 filters presses with productivity of $70m^3/h$ for the process 5.1

3.3. Options for energy integration process

3.3.1. Scheme, providing heat integration

According to the technological regulation there are processes requiring the use of energy from the outside (STEAM, CW20, CW5) for heating and cooling. The problem of the reduction of external energy can be realized through suitable scheme of heat integration. For this case, the use of scheme of Fig.1 is proposed.

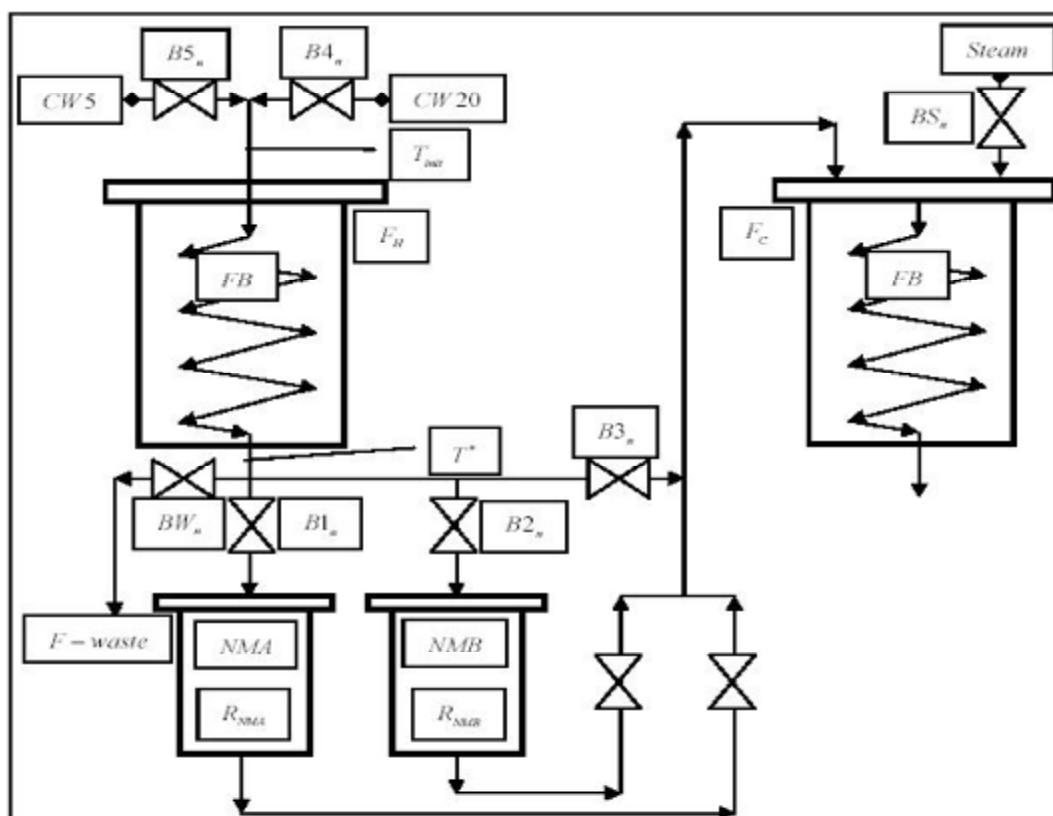


Fig.1 Structure of the scheme for heat integration into a system of batch bioreactors

We will consider the hot reactor as a fermentation reactor F_H in which the processes of raw materials loading and sterilization are completed (3.1-3.7). At the end of 3.7 the mixture in the fermentation reactor is with a temperature $120^\circ C$. After this process is necessary to be carried out cooling process (3.8, 3.9) to temperature $30^\circ C$. To be able to use the available energy of hot reactor it is necessary for the organization of work in the bioreactors system to be such that in the interval of time when you need to be cooled hot reactor F_H to be drawn for sterilization another reactor, which we will treat as cool reactor F_C . In the cool reactor all the processes of loading raw materials have completed

(3.1-3.5) and in their final the mixture with a volume $42m^3$ is with temperature T_3^* . This mixture in the cool reactor subject is to be under heating (3.6, 3.7) and subsequent sterilization (3.8).

3.3.2 Organization of the processes during time

In Figure 2. is shown the Gantt chart for the organization of processes in 2 directions: during time and of the equipment of the scheme in Figure 1.

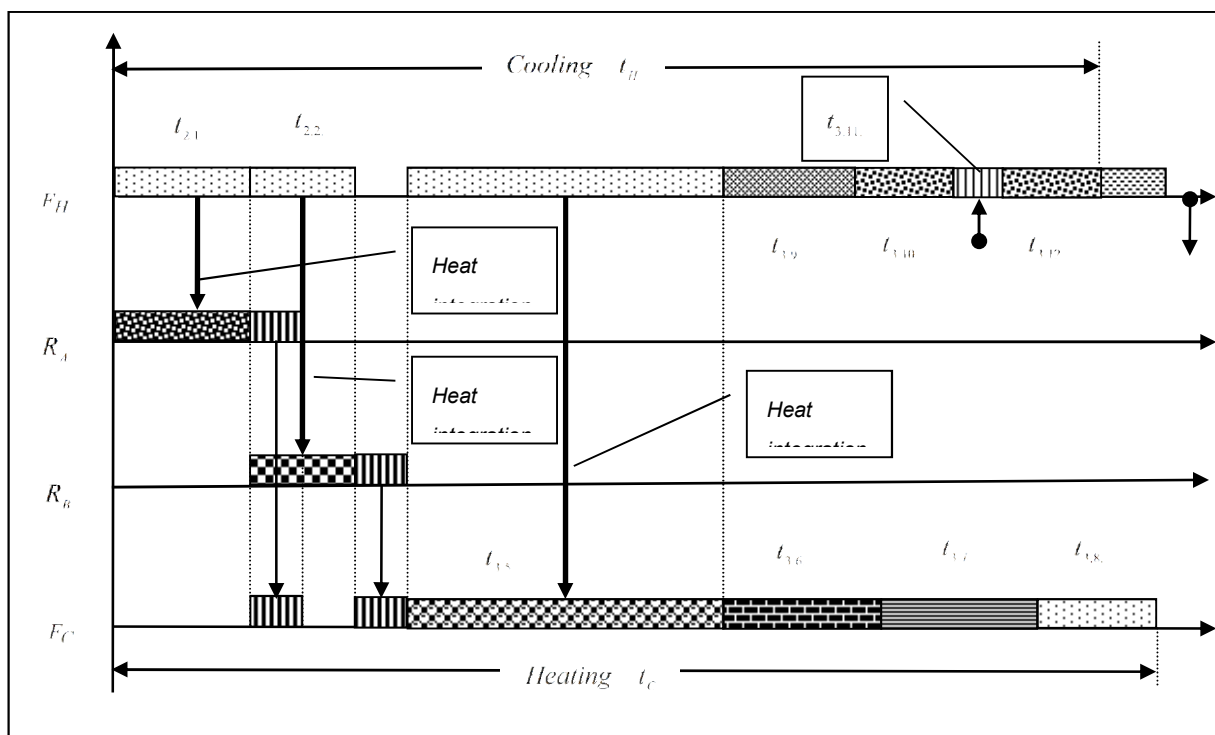


Fig. 2. Gantt chart for the organization of processes

4. MATHEMATICAL FORMULATION OF THE PROBLEM

4.1. Optimal management of processes in the system with heat integration

4.1.1. Processes mathematical modeling

Mathematical description of the process will include processes of heat transfer and mass transfer at time. The equation describing the change in temperature of the mixture in the reactor (F_H) when crossing the flow $CW20$ or $CW5$ determining debit is described by the equation:

$$\frac{dT_F}{dt} = \frac{(\Phi_W - 1)(F_W C_{p_W})}{\Phi_W V_F C_{p_F}} (T_{in} - T_F). \quad (1)$$

Where $\Phi_m = \frac{T_F - T_{in}}{T_F - T^*} = \exp\left(\frac{UA}{F_W C_{p_W}}\right)$, A is heat exchanger surface of the coil with dimension $[m^2]$, and U is overall heat transfer coefficient with dimension $[kWm^{-2}K^{-1}]$, $C_{p_F} = C_F \rho_F$ with

dimension $[kJm^{-3}K^{-1}]$, and C_F according to $[kg/m^3]$, while ρ_F is with dimension $[kg/m^3]$. Flow of cooling water through the coil is F_{wi} is with dimension $[m^3/s]$.

The temperature at the exit of the coil is determined by the equation:

$$T^* = \frac{(\Phi_W - 1)}{\Phi_W} T_F + \frac{1}{\Phi_W} T_{in} \quad (2)$$

The solution of the equation (1) is searched at the start conditions $T_F(0)$. It should be taken into account that the temperature of the water coming out of the coil T^* must be less than the contents in the fermentor T_F ie. $T_F \geq T^*$. Substante NMA is obtained in Stage 2.1., the equations describing the mass change and balance the temperature in the reactor R_{NMA} :

$$\frac{dV_1}{dt} = F_1, \text{ with start conditions } V_1(0) \quad (3)$$

$$Cp_1 V_1 \frac{dT_1}{dt} = F_1 Cp_1 (T^* - T_1), \text{ with start conditions } T_1(0) \quad (4)$$

$Cp_1 = C_1 \rho_1$ with dimension $[kJm^{-3}K^{-1}]$, and C_1 according to $[kJkg^{-1}K^{-1}]$, while ρ_1 is with dimension $[kg/m^3]$.

Substante NMB is obtained in Stage 2.1., the equations describing the mass change and balance the temperature in the reactor R_{NMB} :

$$\frac{dV_2}{dt} = F_2, \text{ with start conditions } V_2(0) \quad (5)$$

$$Cp_2 V_2 \frac{dT_2}{dt} = F_2 Cp_2 (T^* - T_2), \text{ with start conditions } T_2(0) \quad (6)$$

$Cp_2 = C_2 \rho_2$ with dimension $[kJm^{-3}K^{-1}]$, and C_2 according to $[kJkg^{-1}K^{-1}]$, while ρ_2 is with dimension $[kg/m^3]$.

The process of the addition water $17m^3 - 18m^3$ is carried to Stage 3.5.

Mass balance for the case is described by equation:

$$\frac{dV_3}{dt} = F_3, \text{ with start conditional } V_3(0) \quad (7)$$

Positive energy balance is slightly different from those above because it includes a variable start temperature T_{3init} :

$$Cp_3 V_3 \frac{dT_3}{dt} = F_3 Cp_3 (T^* - T_3 - T_{3init}), \quad (8)$$

$Cp_3 = C_3\rho_3$ with dimension $[kJm^{-3}K^{-1}]$, and C_3 according to $[kJkg^{-1}K^{-1}]$, while ρ_3 is with dimension $[kg/m^3]$.

The starting temperature is determined by the equation:

$$T_{3init} = \frac{100V_1(t_f) + V_2(t_f)T_2(t_f)}{V_3(0)}. \quad (9)$$

The equations describing the parameters of the mixtures obtained as a result from mixing of substrate and the receiving water after the coil is given by the equations:

$$F_w = F_{20} + F_5 \quad (10)$$

$$T_{in}F_w = T_{w20}F_{20} + T_{w5}F_5 \quad (11)$$

Determining the price of used water in and for the carrying out of the processes is through integration of the processes, described by the equations shown below.

For $CW5$ equation is:

$$\frac{dWC_5}{dt} = C_{w5}Cp_{w5}F_5(T^* - T_5) \quad (12)$$

with start condition $WC_5(0) = 0$,

where WC_5 is the price of used quantity $CW5$ at the time of process, and C_{w5} is the price per unit energy of $CW5$. Similarly write the equation for determining the price for used water $CW20$.

$$\frac{dWC_{20}}{dt} = C_{w20}F_{20} \quad (13)$$

with start condition $WC_{20}(0) = 0$, where C_{w20} is with dimension $[lw/m^3]$.

4.1.2. Control variables

A multitude of control effects on the case are:

$$\text{Control variables} \rightarrow \left\{ F_w(t), F_1(t), F_2(t), F_3(t), F_4(t) \right. \\ \left. t_{2.1}, t_{2.2}, t_{3.1}, t_{3.5}, t_{3.6}, t_{3.7}, t_{3.8}, t_{3.9}, t_{3.10} \right\}, \quad (14)$$

where $t \in [0, (t_{2.1}, t_{2.2}, t_{3.1}, t_{3.5}, t_{3.6}, t_{3.7}, t_{3.8}, t_{3.9}, t_{3.10})]$

The control variables in the general case are time functions which must be defined. Generally the structure of these functions is well in advance to be set and the task of determining these functions will be limited to determining the coefficients of the given structure. One of the possible structures is:

$$F_i = A_i + (B_i - A_i)\exp(-C_it), \quad i \in I$$

4.1.3. Constraints

The general debit of water at any time is limited as follows:

$$F_1 + F_2 + F_3 + F_{waste} \leq F_w \quad (15)$$

$$F_{waste} \geq 0 \quad (16)$$

$$F_w^{\min} \leq F_w \leq F_w^{\max} \quad (17)$$

Operation of the system is required to meet certain mass and temperature of the mixture attained at the end of the process:

$$V_1(t_{2.1.}) \leq 12m^3 \quad (18)$$

$$V_2(t_{2.2.}) \leq 12m^3 \quad (19)$$

$$V_3(t_{3.5.}) \leq 42m^3 \quad (20)$$

$$T_F(t_{HOT}) \leq 30^\circ C \quad (21)$$

where

$$t_{HOT} = t_{2.1.} + t_{2.2.} + t_{3.1.} + t_{3.5.} + t_{3.9.} + t_{3.10.}$$

Time interval to carry out processes must be such as to satisfy the conditions:

$$t_{2.1.} + t_{2.2.} + t_{3.1.} + t_{3.5.} + t_{3.9.} + t_{3.10.} \leq t_H$$

$$t_{2.1.} + t_{2.2.} + t_{3.1.} + t_{3.5.} + t_{3.6.} + t_{3.7.} + t_{3.8.} \leq t_C$$

where t_H, t_C are given by the conditions of the technology. The problem of determining the optimal control effects are limited to the fact that they must provide a minimum cost for using energy from external sources to carrying out the processes according technological regulation. The dependence to determining the price of using energy is determined according expression that represents the objective function.

4.1.4. Aims of the management

The problem of the optimal management of the processes of heat integration is limited to find the values of control variables (14) providing a minimum cost for using energy from external sources. The objective function is determined by the dependence:

$$F = COST_{Steam} + C_5(t_f) + C_{20}(t_f) \quad (22)$$

where

$$COST_{Steam} = (M_1(t_f) \rho_1 C_{p1} (100 - T_1(t_f)) M_3(t_f) \rho_3 C_{p3} (120 - T_3(t_f) - T_{3init})), \text{ a and } C_{20}(t_f)$$

as a solution on (13).

4.1.5. Optimal control effects

In this formulation of the task the optimal management is limited to determine the multiple control functions (14) providing a minimum of objective function (22) subject to system constraints. This task is a task of the nonlinear dynamic programming. For its solution requires special tools such as gPROMS. The received control impacts in the form of time functions are difficult to be implemented because they require use of complex regulatory systems. It should also be taken into account that used

parameters in the models may change over time or be set incorrectly, which leads to the determination of control functions not leading to management purposes (22).

4.2. Quasioptimal management of the processes in a system with heat integration.

Another approach to control effects ensuring the purposes of managing will be discussed below. This approach is based on the following assumptions.

1. The process of heat integration for the time t_f is treated as at the $N = 8$ time interval (for each one of the boolean control variables to be provided at the one time interval)
2. During every time interval the parameters of the control variables do not change.

4.2.1. Mathematical model of the processes by quasioptimal management.

Instead the differential equations describing the processes we can use for $\forall n \in [1, N]$ their interval decisions that for each of the intervals are of the form/as follows:

$$T_{Fn}(t) = (T_{in})_n + ((T_{F0})_{(n-1)} - (T_{in})_n) \exp(-p_n t), \quad (23)$$

$$T_{Wn}^*(t) = (T_{in})_n + \frac{(\Phi_{Wn} - 1)}{\Phi_{Wn}} ((T_{F0})_{(n-1)} - (T_{in})_n) \exp(-p_n t), \quad (24)$$

$$\text{where } \Phi_{Wn} = \exp\left(\frac{UA}{F_{Wn} Cp_{Wn}}\right), \quad p_n = \frac{F_{Wn} Cp_{Wn} (\Phi_{Wn} - 1)}{\Phi_{Wn} V_F Cp_F}.$$

Using (23) and (24) the equations for each one of the intervals can be determined by substituting values for the parameters of water input in the coil, the debit and the start conditions, for each of the intervals will be:

Interval 1. The data for this interval are: $n = 1$, $t_n = t_1$, $B1_n = 1$, $B2_n = 0$, $B3_n = 0$, $B4_n = 1$, $B5_n = 0$ during which is carried out Step 2.1 in the reactor R_{NMA} and Step 3.9 in the reactor F_H .

The function of the change of the temperature in hot reactor F_H is described by the equation (23), and the change of the temperature in output water from the coil (24) with the following formulations

$$(T_{in})_n = B5_n T_{W5} + B4_n T_{W20}, \quad (25)$$

$$Cp_{Wn} = B5_n Cp_{W5} + B4_n Cp_{W20}, \quad (26)$$

$$F_{Wn} = F_{W1}, \quad (T_{F0})_{(n-1)} = T_{F0}.$$

Also it is necessary to observe and the restriction to the maximum quantity of water necessary for the process i. e.

$$F_{W1} t_1 (1 - BW_1) = B1_1 V_{2.1} + B2_1 V_{2.2} + B3_1 V_{3.5}. \quad (27)$$

The temperature in the received mixture is given by the decision of the system of equations (3) and (4) has the form:

$$T_{NBA}(t) = A - B \exp(-p_n t), \quad (28)$$

where ,

$$A = \frac{(p_n T_{NBA}(0) V_{NBA}(0) + F_{Wn} A_{pn} + F_{Wn} (T_{in})_n p_n t)}{p_n (F_{Wn} t + V_{NBA}(0))},$$

$$B = \frac{F_{Wn} A_{pn}}{p_n (F_{Wn} t + V_{NBA}(0))}, \quad p_n = \frac{(\Phi_{Wn} - 1) F_{Wn} C p_{Wn}}{\Phi_{Wn} V_F C p_F},$$

$$A_{pn} = \frac{(\Phi_{Wn} - 1)(T_{F0} - (T_{in})_n)}{\Phi_{Wn}}, \quad \Phi_{Wn} = \exp\left(\frac{UA}{F_{Wn} C p_{Wn}}\right).$$

According the requirements of the technology at the end of the time interval $t = t_1$ should be add water from the cooling coil volume $V_{2.1}$. The time for carry out of this stage would be $t_1 = \frac{V_{2.1}}{F_{Wn}}$, the resulting mixture NBA is with a volume $V_{NBA} = (V_{2.1} + V_{NBA}(0))$, and respectively with the temperature at the end of the interval $T_{NBA}(t_1) = T_{NBA}^*$ defined from (28) by $t = t_1$, $F_{Wn} = F_{W1}$. At the same time as a result of the process Step 3.9. the contents in the reactor F_H is reached a temperature T_{F1}^* which is determined by (23) and $t = t_1$.

Interval 2. The data for this interval are: $n = 2$, $t_n = t_2$, $B1_n = 0$, $B2_n = 1$, $B3_n = 0$, $B4_n = 1$, $B5_n = 0$, $BW_n = 0$, $BS_n = 0$ during which is carried out Step 2.2 in the reactor R_{NMB} and Step 3.9 in the reactor F_H .

And here the function of the change of the temperature in hot reactor F_H is described by the equation (23), and the change of the temperature in output water from the coil (24) with the following formulations $(T_{in})_n \rightarrow (25)$, $Cp_{Wn} \rightarrow (26)$, $F_{Wn} = F_{W2}$, $(T_{F0})_{(n-1)} = T_{F1}^*$. Also it is necessary to observe and the restriction to the maximum quantity of water necessary for the process i. e.

$$F_{Wn} t_n (1 - BW_n) = B11 + B12 + B13. \quad (29)$$

$$B11 = B1_n \left(V_{2.1} - \sum_{m=1}^{(n-1)} B1_m F_{Wm} t_m \right),$$

$$B12 = B2_n \left(V_{2.2} - \sum_{m=1}^{(n-1)} B2_m F_{Wm} t_m \right),$$

$$B13 = B3_n \left(V_{3.5} - \sum_{m=1}^{(n-1)} B3_m F_{Wm} t_m \right)$$

The temperature in the received mixture NBB is determined by (30), which is the decision of the system of equations (5) and (6) has the form $T_{NBB}(t) = C - D \exp(-p_n t)$, (30)

$$\text{where } C = \frac{(p_n T_{NBB}(0) V_{NBB}(0) + F_{Wn} A_{pn} + F_{Wn} (T_{in})_n p_n t)}{p_n (F_{Wn} t + V_{NBB}(0))}, D = \frac{F_{Wn} A_{pn}}{p_n (F_{Wn} t + V_{NBB}(0))},$$

$$\Phi_{Wn} = \exp\left(\frac{UA}{F_{Wn} C p_{Wn}}\right), p_n = \frac{(\Phi_{Wn} - 1) F_{Wn} C p_{Wn}}{\Phi_{Wn} V_F C p_F}, A_{pn} = \frac{(\Phi_{Wn} - 1)(T_{F1}^* - (T_{in})_n)}{\Phi_{Wn}}.$$

At the end of time interval $t = t_2$, should be added water from the cooling coil with volume $V_{2.2}$. The time for carry out of this stage would be $t_2 = \frac{V_{2.2}}{F_{Wn}}$ the resulting mixture NBB is with volume $V_{NBB} = (V_{2.2} + V_{NBB}(0))$ and respectively with the temperature at the end of the interval $T_{NBB}(t_2) = T_{NBB}^*$ defined from (30) by $t = t_2$, $F_{Wn} = F_{W2}$. At the same time as a result of the process Step 3.9. the contents in the reactor F_H is reached a temperature T_{F2}^* which is determined by (23) and $t = t_2$, $n = 2$.

Interval 3. During this interval is carried out Step 3.1. and Step 3.2. in the reactor F_C by the following data: $n = 3$, $t_n = t_3$, $B1_n = 0$, $B2_n = 0$, $B3_n = 0$, $B4_n = 0$, $B5_n = 0$, $BW_n = 0$, $BS_n = 1$, $T_{F3}^* = T_{F2}^*$

In this time interval is carried out the process of the transfer of NBA in the reactor F_C and then heating to a temperature $T_{st.}$ and sterilization. This process is carried out with the use of steam as a coolant. The energy required to carry out the process is determined through dependence:

$$E_{33.} = C p_{NBA} V_{NBA} (T_{st.} - T_{NBA}^*) \quad (31)$$

where $T_{st.}$, $V_{NBA} = (V_{2.1} + V_{NBA}(0))$ is the temperature of the sterilization of the mixture NBA , and T_{NBA}^* is the temperature of the mixture at the end of the Interval 1 which is determined with the help of (28) by $t = t_1$, $C p_{NBA} = C_{NBA} \rho_{NBA}$ with dimension $[kJm^{-3}K^{-1}]$, and C_{NBA} respectively $[kJkg^{-1}K^{-1}]$, while ρ_{NBA} is with dimension $[kg/m^3]$, $E_{3.3}$ is with dimension $[kJ]$.

Interval 4. During this interval is carried out Step 3.4 in the reactor F_C by the following data: $n = 4$, $t_n = t_4$, $B1_n = 0$, $B2_n = 0$, $B3_n = 0$, $B4_n = 0$, $B5_n = 0$, $BW_n = 0$, $BS_n = 0$, $F_{Wn} = F_{W4} = 0$, $T_{F4}^* = T_{F2}^*$

In this time interval is carried out mixing process the mixture NBA in F_C after the sterilization at a temperature $T_{st.}$ (Step 3.2.) and transfer in the same reactor F_C of NBB which is with a temperature T_{NBB}^* with a subsequent mixing for 1 hour, i.e. $t_n = t_4$. The temperature of the resulting mixture with

a volume $V_{AB} = V_{NBA} + V_{NBB}$ is determined by the dependence $T_{AB}^* = \frac{V_{NBA} T_{st.} + V_{NBB} T_{NBB}^*}{V_{AB}}$.

Interval 5. The data for this interval are: $n = 5, t_n = t_5, B1_n = 0, B2_n = 0, B3_n = 1, B4_n = 1, B5_n = 0, BW_n = 0, BS_n = 0$ during which is carried out Step 3.9 in the reactor F_H and Step 3.5 in the reactor F_C .

The function of change of the temperature of the hot reactor is described by equation (23) and the change of the temperature output water from a coil (24) by $(T_{in})_n \rightarrow (25), Cp_{Wn} \rightarrow (26), F_{Wn} = F_{W5}, (T_{F0})_{(n-1)} = T_{F4}^*$. In this case T_{F4}^* is the temperature of the hot reactor F_H at the end of Interval 4, $n = 4$. Moreover, the restriction on the maximum quantity of water for the process must satisfy equality (29). The temperature of the received mixture $T_3(t) (NMAB = AB IAB + CW20^*) (CW20^*$ is the water added in F_C output of the coil of F_H) is the solution of the system of equations (7) and (8) has the form:

$$T_3(t) = \frac{(p_n V_{AB} T_{AB}^* + F_{Wn} A_{Pn} + p_n F_{Wn} (T_{in})_n t)}{p_n (F_{Wn} t + V_{AB})} - \frac{F_{Wn} A_{Pn}}{p_n (F_{Wn} t + V_{AB})} \exp(-p_n t), \quad (32)$$

$$\text{where } \Phi_{Wn} = \exp\left(\frac{UA}{F_{Wn} Cp_{Wn}}\right), p_n = \frac{(\Phi_{Wn} - 1)F_{Wn} Cp_{Wn}}{\Phi_{Wn} V_F Cp_F}, A_{Pn} = \frac{(\Phi_{Wn} - 1)(T_{F4}^* - (T_{in})_n)}{\Phi_{Wn}}.$$

According the requirements of the technology at the end of the time interval $t = t_5$ should be added water from the cooling coil with volume $V_{3.5}$.

Under this condition, the timing for carry out of this stage will be $t_5 = \frac{V_{3.5}}{F_{Wn}}$ the resulting mixture $NMAB$ is with volume $V_{NMAB} = (V_{3.5} + V_{AB})$ and according with temperature at the end of the interval T_3^* defined through (32) by $t = t_5, F_{Wn} = F_{W5}$. At the same time the temperature of the hot reactor F_H at the end of the interval reached a value T_{F5}^* fixed from (23).

Interval 6. The data for this interval are: $n = 6, t_n = t_6, B1_n = 0, B2_n = 0, B3_n = 0, B4_n = 1, B5_n = 0, BW_n = 1, BS_n = 0$ during which is carried out Step 3.9 in the reactor F_H .

The function of change of the temperature of the hot reactor F_H is described by equation (23) and the change of the temperature output water from a coil (24) by $(T_{in})_n \rightarrow (25), Cp_{Wn} \rightarrow (26), F_{Wn} = F_{W6}, (T_{F0})_{(n-1)} = T_{F5}^*$. In this case the temperature of the hot reactor F_H at the end of Interval 6 by $t_n = t_6$ definite by (23) is T_{F6}^* . The equation for determining the current temperature of the cooling water output from the coil is modify and acquires the type:

$$T_{W6}^*(t) = T_{W20} + \frac{(\Phi_{W6} - 1)}{\Phi_{W6}} (T_{F5}^* - T_{W20}) \exp(-p_6 t), \quad (33)$$

$$\text{where } \Phi_{W6} = \exp\left(\frac{UA}{F_{W6} Cp_{W20}}\right), p_6 = \frac{F_{W6} Cp_{W20} (\Phi_{W6} - 1)}{\Phi_{W6} V_F Cp_F}.$$

Interval 7. The data for this interval are: $n = 7$, $t_n = t_5$, $B1_n = 0$, $B2_n = 0$, $B3_n = 0$, $B4_n = 0$, $B5_n = 1$, $BW_n = 1$, $BS_n = 0$ $n = 7$ during which is carried out Step 3.9 in the reactor F_H .

And here the function of change of the temperature of the hot reactor F_H is described by equation (23) and the change of the temperature output water from a coil (24) by $(T_{in})_n \rightarrow (25)$, $Cp_{Wn} \rightarrow (26)$, $F_{Wn} = F_{W6}$, $(T_{F0})_{(n-1)} = T_{F5}^*$. In this case the temperature of the hot reactor F_H at the end of Interval 7 by $t_n = t_7$ definite by (23) is T_F^* . The equation for determining the current temperature of the cooling water output from the coil is modify and acquires the type:

$$T_{W7}^*(t) = T_{W5} + \frac{(\Phi_{W7} - 1)}{\Phi_{W7}} (T_{F6}^* - T_{W5}) \exp(-p_7 t), \quad (34)$$

$$\text{where } \Phi_{W7} = \exp\left(\frac{UA}{F_{W7} Cp_{W5}}\right), \quad p_7 = \frac{F_{W7} Cp_{W5} (\Phi_{W7} - 1)}{\Phi_{W7} V_F Cp_F}.$$

Interval 8. The data for this interval are: $n = 8$, $t_n = t_7$, $B1_n = 0$, $B2_n = 0$, $B3_n = 0$, $B4_n = 0$, $B5_n = 0$, $BW_n = 0$, $BS_n = 1$ during which is carried out Step 3.6., Step 3.7. and Step 3.8 in the reactor F_C

In this time interval is carried out the process of heating of $NMAB$ in the reactor F_C to temperature T_{st} and sterilization by temperature T_{st}^* using steam. The necessary energy to carry out the process is determined by the dependence:

$$E_{3.8} = Cp_{NMBA} V_{NMBA} (T_{st}^* - T_3^*) \quad (35)$$

where T_{st}^* is the temperature of the sterilization of the mixture $NMAB$ with volume V_{NMBA} , T_3^* is the temperature of the mixture at the end of the interval 5 defined through (32) by $t = t_5$,

$Cp_{NMBA} = C_{NMBA} \rho_{NMBA}$ with dimension $[kJm^{-3}K^{-1}]$ and C_{NMBA} according $[kJkg^{-1}K^{-1}]$, while ρ_{NMBA} is with dimension $[kg/m^3]$, $E_{3.8}$ is with dimension $[kJ]$.

4.2.2. Control variables

In this formulation as control variables instead of multiple functions (14) will we have multiple parameters corresponding to each time interval ie:

$$\text{Control continues variables} \rightarrow \{t_n, F_{Wn}, F_{1n}, F_{2n}, F_{3n}\}, \quad n \in [1, N] \quad (36)$$

Moreover, we introduce in addition and the following multitudes Binary variables:

$$\text{Control Binary variables} \rightarrow \{BW_n, B1_n, B2_n, B3_n, B4_n, B5_n\}, \quad n \in [1, N] \quad (37)$$

where $BW_n = 1$ when in n^{th} time interval corresponding valve is opened and is closed by $BW_n = 0$. The same conditions are valid for the other Binary variables $\{B1_n, B2_n, B3_n, B4_n, B5_n\}$, $n \in [1, N]$.

By entering binary variables for the control the flow of cooling water continuous independent variables can be reduced by substituting with their equivalents ie

$$(F_{Waste})_n = BW_n F_{Wn}, F_{1n} = B1_n F_{Wn}, F_{2n} = B2_n F_{Wn}, F_{3n} = B3_n F_{Wn}$$

In this formulation the multitude of control variables will be:

$$\text{Control continues variables} \rightarrow \{t_n, F_{Wn}\}, \quad n \in [1, N]$$

4.2.3. Constraints

The time restriction are related with the conditions to carry out of the individual processes dictated by technological requirements. The processes related with cooling of the hot reactor after its sterilization must be carried out under conditions that satisfy the restriction:

$$\frac{V_{21}}{F_{W1}} + \frac{V_{22}}{F_{W2}} + MAX\left\{\frac{V_{22}}{F_{W2}}, t_3\right\} + \frac{V_{35}}{F_{W5}} + t_5 + t_6 + t_7 \leq t_C, \quad (38)$$

where t_C is the allowed time for carrying out the process of cooling the hot reactor F_H from temperature T_{st}^* until working temperature for the fermentation process T_{fer} and t_3 whili t_C .

At the same time the processes related to preparation of the substrate in the fermentation reactor and heated to a temperature of sterilization with subsequent sterilization must be carried out at the time satisfying the restriction:

$$t_3 + \frac{V_{3.5}}{F_{W5}} + t_{3.6} + t_{3.7} + t_{3.8} \leq t_H \quad (39)$$

To ensuring for condition the functioning of system when in each time interval to run only one process and also do not allow at the same time use of $CW20$ and $CW5$ need to satisfy the binary variables and system restriction.

$$\left. \begin{array}{l} BW_n + B1_n + B2_n + B3_n \leq 1 \\ B5_n + B4_n \leq 1 \\ B5_n + B1_n + B2_n + B3_n \leq 1 \end{array} \right\}, \forall n \in [1, N]$$

4.2.4. Aims of the management

The main aim by carrying out of the process in hot and cold reactors through the system of heat integration process is to reduce the price of the used energy resources (heat and cold) to carrying out of the heating and cooling processes. Namely this indicator will be used as a criterion to assess of the conducted processes management.

$$Cost_{INT} = \sum_{n=1}^{N=8} Cost_n \quad (41)$$

where $Cost_n$ is the price of the used energy resources to carry out of the processes for each of time intervals and is determined according to the expressions:

$$Cost_1 = Cost_2 = Cost_4 = Cost_5 = 0, \quad Cost_3 = C_{Steam} E_{3.3}.$$

$$Cost_6 = C_{W20} F_{W6} t_6, \quad Cost_7 = C_{W5} C p_{W5} V_F \int_{t=0}^{t=t_7} (T_{W7}^*(t) - T_{W5}) dt = \frac{C_{W5} C p_{W5} V_F A_{W7}}{p_7} (1 - \exp(-p_7 t_7))$$

$$\text{where } A_{W7} = \frac{(\Phi_{W7} - 1)}{\Phi_{W7}} (T_{F6}^* - T_{W5}), \quad \Phi_{W7} = \exp\left(\frac{UA}{F_{W7} C p_{W5}}\right), \quad p_7 = \frac{F_{W7} C p_{W5} (\Phi_{W7} - 1)}{\Phi_{W7} V_F C p_F},$$

$$T_{W5} = 5^\circ C, \quad Cost_8 = C_{Steam} E_{3.8}.$$

where C_{W20} is the price of the water $CW20$, C_{W5} and of the water $CW5$, $C p_{W5}$ is a specific heat capacity of cooling water C_{W5} , T_{F6}^* is the temperature of the hot reactor at the end of the sixth time interval, $E_{3.8}$ the required energy for heating until temperature T_{st}^* and subsequent sterilization with steam, which is determined by (35).

4.2.5. Quasioptimal control effects

The problem of optimal control can be formulated as follows. Searching for values of control variables (36), which ensure minimum of the objective function (41) by observing to system restriction, (38) (39). So formulated task is solved with the use of any of the methods for nonlinear programming (NLP).

4.3. Optimal control for the system without heat integration

The processes "cooling" of the hot reactor and respectively preparation and sterilization of the cool reactor are the main processes requiring energy from outside. The cooling of the hot reactor after sterilization is carried out in two steps, namely cooling until a temperature $40^\circ C$ with technical water $CW20$ for time t_{W20} and after that to cooling until a temperature $30^\circ C$ for time t_{W5} with help of the cooled water. The times to carry out of the cooling processes t_{W20} and t_{W5} subject to the determination. According to the technological regulation these two processes are carried out for the time $t_{W20} + t_{W5} \leq t_f$. Using the above obtained dependences describing the cooling and heating processes can be easily defined optimal control effects (in the case the debits of the cooling water $CW20 \rightarrow F_{W20}$ and according for $CW5 \rightarrow F_{W5}$, and also the times to carry out of these two processes t_{W20} and t_{W5}) which ensure carrying out of the processes by minimum cost criterion of resource used for cooling (water $CW20$ and $CW5$).

1. The price to carry out of the cooling process with $CW20$ is:

$$Cost_{W20} = C_{W20} F_{W20} t_{W20}$$

2. The price to carry out of the cooling process with $CW5$ is determined by:

$$Cost_{W5} = C_{W5} C p_{W5} V_H \int_{t=0}^{t=t_5} (T_{F20}(t) - T_{W5}) dt = \frac{C_{W5} C p_{W5} V_F A_{W5}}{p_5} (1 - \exp(-p_5 t_5))$$

$$\text{where } A_{W5} = \frac{(\Phi_{W5} - 1)}{\Phi_{W5}} (T_{F20}^* - T_{W5}), \quad \Phi_{W5} = \exp\left(\frac{UA}{F_{W5} C p_{W5}}\right), \quad p_5 = \frac{F_{W5} C p_{W5} (\Phi_{W5} - 1)}{\Phi_{W5} V_F C p_F},$$

where, and T_{F20}^* is determined through (23) by $n = 2$, $(T_{in})_n = T_{W5}$, $F_{Wn} = F_5$, $c_{wn} = Cp_{W5}$, and $(T_{F0})_{(n-1)}$ is determined through (23) by $n = 1$, $(T_{in})_n = T_{W20}$, $F_{Wn} = F_{20}$, $c_{wn} = Cp_{W20}$, $t = t_{W20}$, and $(T_{F0})_{(n-1)} = T_{F0}$.

The determination of the optimal values of control effects (F_{20} , F_5 , t_{20} , t_5) can be done by formulating the task of nonlinear mathematical programming as follows:

It is demand a minimum of objective function:

$$Cost_{water} = Cost_{W20} + Cost_{W5}$$

in terms of control variables $\{F_{W20}, F_{5W}, t_{W20}, t_{W5}\}$ by performance of system restriction:

$$\left. \begin{aligned} (t_{W20} + t_{W5}) &\leq t_f \\ F_{W5} &\leq F_{W5}^{MAX} \\ F_{W20} &\leq F_{W20}^{MAX} \\ T_{F5}^*(t_5) &\leq 30^\circ C \end{aligned} \right\}$$

So formulated task is of the class of tasks of nonlinear mathematical programming with continuous control variables.

The processes related with the preparation of raw material (Stage 2.1 и 2.2), mixing, adding of $V_{3.5}$, cool water $CW20$ (Stage 3.5), used as energy source steam with volume $3.5bar$. The energy used for these processes are defined as follows:

$$\left. \begin{aligned} E_{3.2} &= Cp_1 V_{2.1} \rho_1 (T_{3.1} - T_{W20}) \\ E_{3.3} &= Cp_1 V_{2.1} \rho_1 (T_{st.} - T_{3.1}) \\ E_{3.4} &= Cp_2 V_{2.2} \rho_2 (T_{st.}^* - T_{W20}) \\ E_{3.6} &= Cp_3 V_{3.5} \rho_3 (T_{st.}^* - T_{W20}) \end{aligned} \right\} \text{ with use of steam.}$$

The price for using steam for the carrying out of the these processes is equal to:

$$Cost_{steam} = C_{steam} (E_{3.2} + E_{3.3} + E_{3.4} + E_{3.6})$$

In this formulation the total price for using energy to carry out of the processes of the raw material preparation, heating, sterilization and cooling to required Working temperature to carry out of the fermentation process is equal to:

$$Cost_{SUM} = Cost_{Steam} + Cost_{Water}$$

5. AN EXAMPLE IN SUPPORT OF THE PROCEDURE

As an example, proving the feasibility of the proposed method of management is considering a system for the production of antibiotics. It is carried out in batch reactors by sequence of processes as described in 3.1. The data of the processes are given:

$$Cp_F = Cp_{W5} = Cp_{W20} = Cp_1 = Cp_2 = Cp_3 = Cp_{NMB A} = 4200 \text{ kJm}^{-3} \text{K}^{-1}, \quad V_F = V_{NMA B} = 42 \text{ m}^3,$$

$$T_F(0) = T_{st}^* = T_{F0} = 120^\circ \text{C}, \quad T_{W5} = 5^\circ \text{C}, \quad T_1(0) = T_2(0) = T_{NBA}(0) = T_{NBB}(0) = T_{W20} = 20^\circ \text{C},$$

$$T_{st} = 100^\circ \text{C}, \quad T_{3.1} = 55^\circ \text{C}, \quad T_F(t_f) = T_{fer} = 30^\circ \text{C}, \quad V_1(0) = V_2(0) = V_{NBA}(0) = V_{NBB}(0) = 2 \text{ m}^3,$$

$$V_{2.1}, V_{2.2} = 10 \text{ m}^3, \quad V_{3.5} = 18 \text{ m}^3, \quad V_{NBA}, V_{NBB} = 12 \text{ m}^3, \quad V_3(0), V_{AB} = 24 \text{ m}^3, \quad t_C = t_f = 6000 \text{ s},$$

$$F_5^{MAX} = F_{20}^{MAX} = 0.04 \text{ m}^3 / \text{s}, \quad U = 1.2 \text{ kWm}^{-2} \text{K}^{-1}, \quad A = 56.55 \text{ m}^2, \quad C_{W5} = (CG_{W5} / 4.184) \text{ lW} / \text{GJ},$$

$$CG_{W5} = 681.00 \text{ lW} / \text{GCal}, \quad CG_{Steamt} = 277.00 \text{ lW} / \text{GCal}, \quad C_{Steam} = (CG_{steam} / 4.184) \text{ lW} / \text{GJ},$$

According to the described methodology are carried out calculations to determine the optimal control effects (F_{W20} , F_{W5} , t_{W20} , t_{W5}) for the case without heat integration integration of the processes. The task of mathematical programming is solved using MATLAB 6.50. The optimal values of control variables for the case without heat integration of processes are given in Tabl.1.

Table 1. Optimal values of control effects for the system without heat integration of the processes

N o	Time of the process sec	Optimal debit of the cooling water m^3 / s		Quantity of the cooling water at the end of the process m^3		Temperature of the reactor at the end of the proces $^\circ \text{C}$
i	t_{in}	F_{W20}	F_{W5}	V_{W20}	V_{W5}	T_{Fi}
1	1158.6	0.0374	0.0	43.3108	0.0	89.6366
2	1158.6	0.0374	0.0	43.3131	0.0	68.4916
3	1158.7	0.0374	0.0	43.3151	0.0	53.7667
4	1158.7	0.0374	0.0	43.3134	0.0	43.5135
5	1365.4	0.0	0.0400	0.0	54.6166	30.0000

In the case when control of the "cooling-heating" process is carried out in continuous time-varying control variables (the debits of cooling liquid through the coil) and is carried out the heat integration of the processes were made calculation using the package MATLAB 6.50. The debits of the cooling flow through the coil to the case is amended as dependency.

$$F_i = A_i + (B_i - A_i) \exp(-C_i t), \quad i \in I, \quad I = \overline{1, 5},$$

where the unknown coefficients (A_i , B_i , C_i) to be determined for each time interval.

In Table 2 are given the obtained optimal values of the control variables resulting from the decision of the optimization procedure to the model described in point 4.1

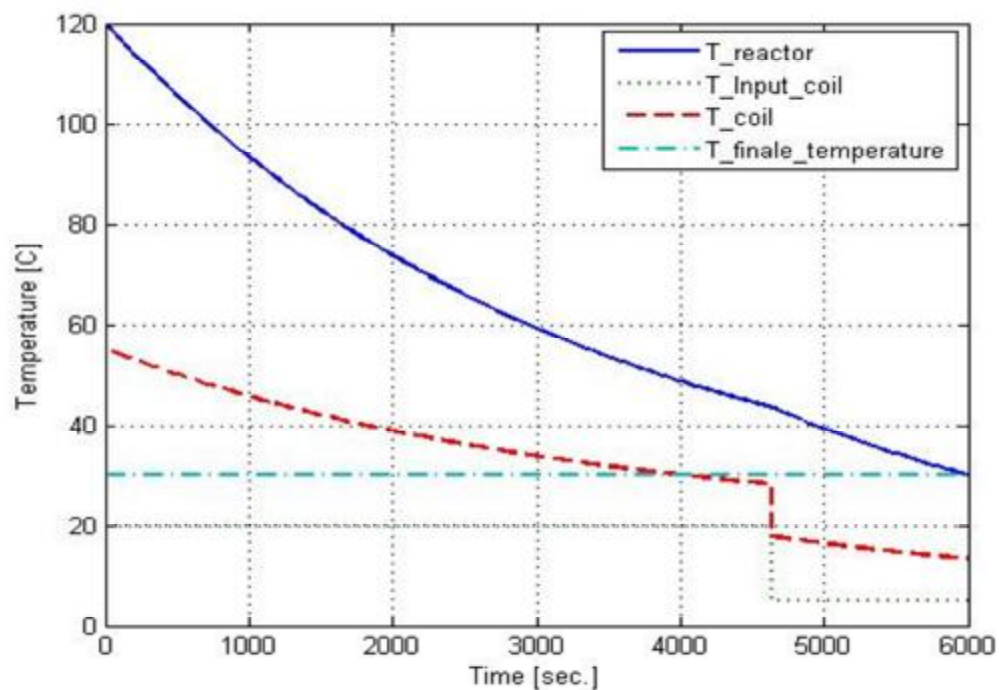


Fig.3. Temperature in the reactor for the case without heat integration

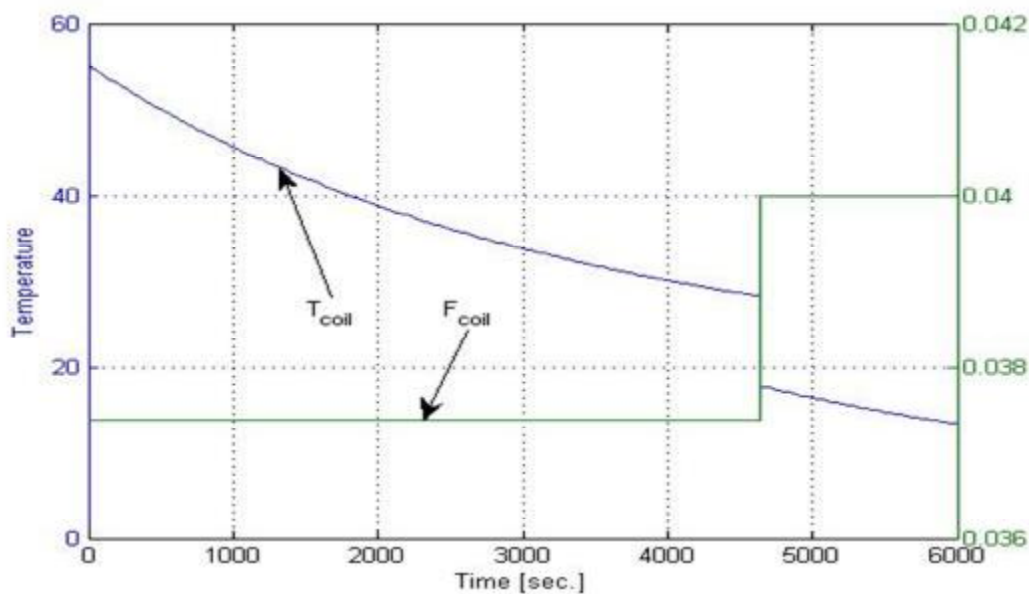


Fig.4. Debits variation of the coolant through the coil to ensure minimum energy costs without heat integration

Table 2. Optimal values of the control effects for the system with heat integration of the processes for continuous variables

No	Time of the process sec.	Optimal values of the parameters determining the debits of the cooling liquid			Quantity of the ciiling liquid m^3		Temperature of the reactor at the end of the intervals $^{\circ}C$
i	t_{in}	A_i	B_i	C_i	V_{20}	V_{CS}	$T_{Fn}(t_{in})$
1	414.32	0.0359	0.0186	0.0020	9.99	0.0	109.06
2	416.09	0.0385	0.0235	1.73e-004	9.99	0.0	99.27
3	1046.80	0.0400	0.0107	5.02e-004	18.00	0.0	81.25
4	2286.50	0.0400	0.0400	0.0074	91.46	0.0	49.70
5	1836.30	0.0400	0.0400	0.0100	0.0	73.45	30.00

In the Fig.3 are shown the variation of the temperature in the reactor and output of the coil at the time intervals for the case of heat integration and continuous control variables.

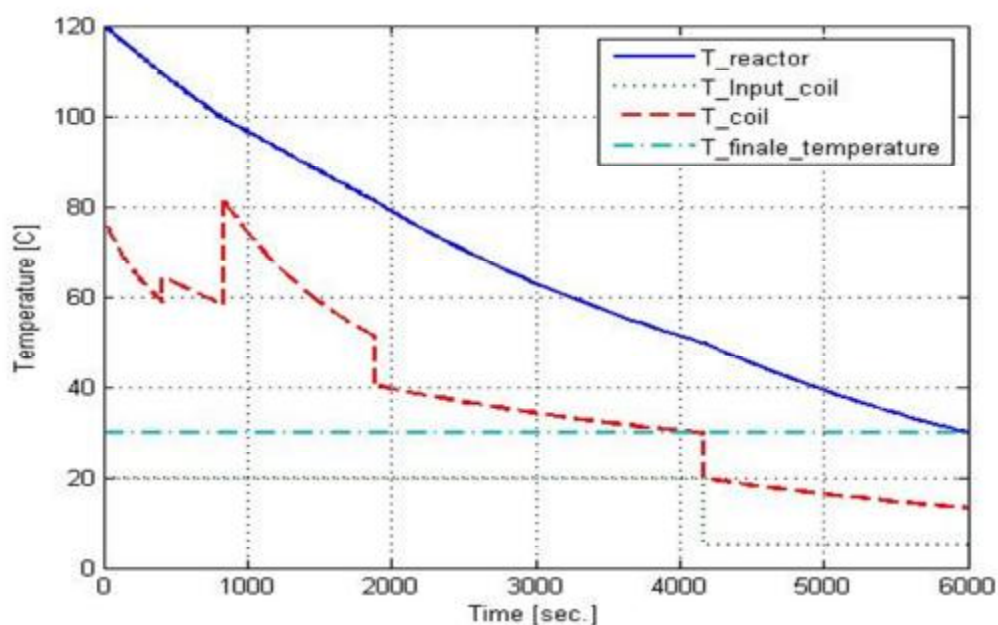


Fig.5. Temperatures variation in the reactor in the case of heat integration and continuous control variables.

Fig.6 shows the optimal values of the debits functions of cooling flow in the time ensuring minimum energy costs during processes "cooling-heating" realization.

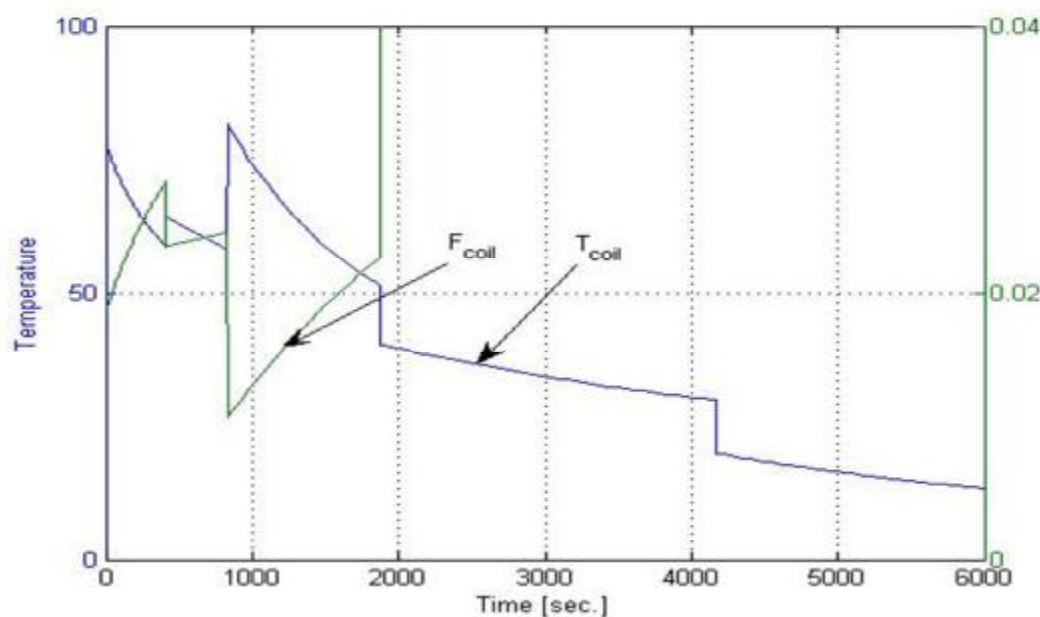


Fig 6. Debits variation of cooling liquid through the coil, ensuring minimum energy costs

In the case when the proposed scheme is used for heat integration of the processes of quasioptimal control the cooling process is using the methodology described in 4.2. For the same process the calculation procedures were carried out using the package MATLAB 6.50. In the case the number of the time intervals is $N_1 = N_2 = N_3 = N_4 = 1$. The obtained optimal control effects for each of the time intervals are given in Table 3.

Table 3. The control effects for the system with heat integration for quasioptimal management

No	Time of the process sec.	Debits of the cooling liquid m^3 / s		Quantity cooling reagent at the time intervals m^3					Temperature of the reactor $^{\circ}C$
i	t_{in}	F_{W20}	F_{C5}	V_1	V_2	V_3	V_W	V_{C5}	T_{Fn}
1	478.3	0.0209	0.0	10.0	0.0	0.0	0.0	0.0	107.97
2	441.2	0.0227	0.0	0.0	10.0	0.0	0.0	0.0	97.91
3	845.5	0.0213	0.0	0.0	0.0	18.0	0.0	0.0	82.03
4	2535.8	0.0400	0.0	0.0	0.0	0.0	101.43	0.0	47.80
5	1699.1	0.0	0.0400	0.0	0.0	0.0	0.0	67.96	30.00

In the Fig.7 are shown the variation of the temperature in the reactor and output of the coil at the time intervals for the case of heat integration and quasioptimal process management..

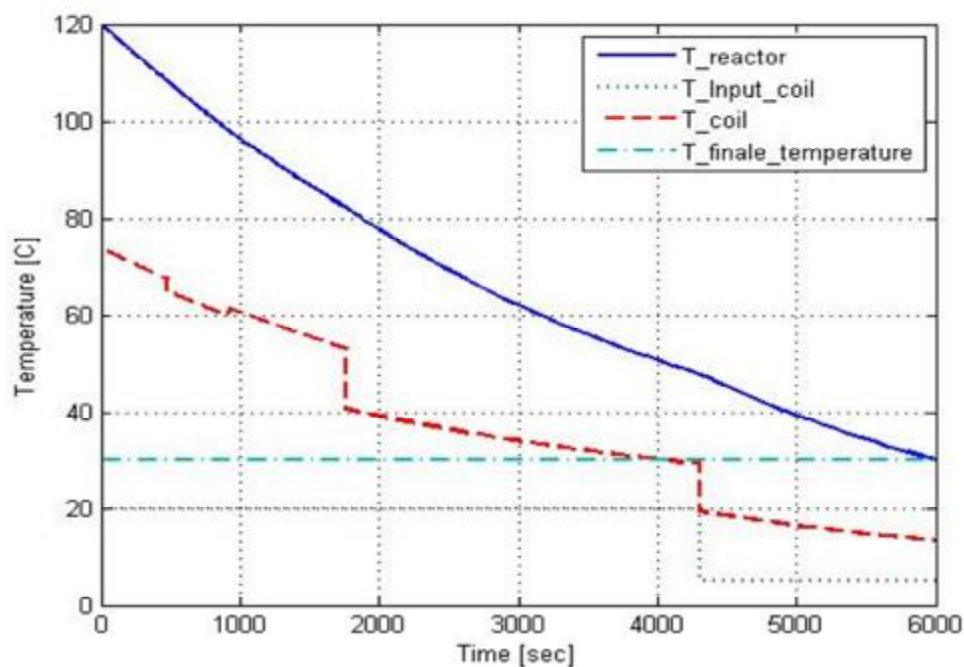


Fig 7. Temperatures variation in the reactor in the case of heat integration and quasioptimal process management

Fig.8 shows the values of the debits functions of cooling flow in the time ensuring minimum energy costs during processes "cooling-heating" realization and quasioptimal process management.

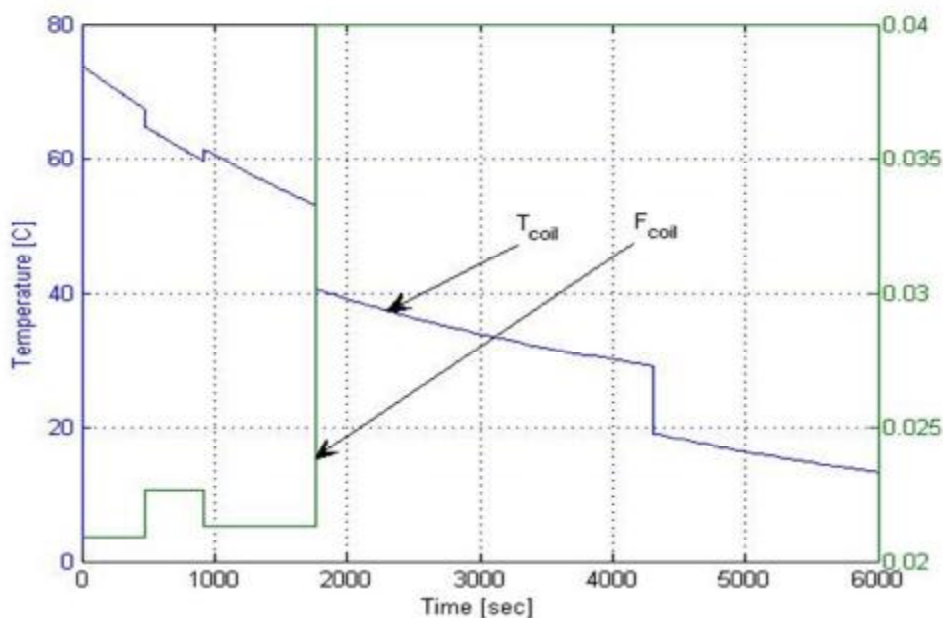


Fig 8. Debits variation of cooling liquid through the coil, ensuring minimum energy costs

The prices of used resources for the processes heating and cooling for the system with heat integration and those for the system without heat with heat integration are given in Table 4.

Table 4. Energy costs of in system with and without heat integration

Type of cost	Costs in absence of heat integration lw .	Costs with heat integration	
		Optimal management lw .	Quasioptimal management lw .
$Cost_{STEAM}$	945.85	715.60	724.81
$Cost_{W20}$	378.38	199.75	221.53
$Cost_{W5}$	388.17	565.98	536.99
$Cost_{SUM}$	1712.4	1481.30	1483.30

It is obviously that the optimal management of the process heat integration leads to significant reduction of about 47.20% of water used $CW20$ in regime of the optimal management and according about 41.45% for quasioptimal management. The costs for cooling water were increased in the case of optimal management with 45.80% and quasioptimal management with 38.15%. At the same time is reduced the needed steam to carry out of the processes with 24.34% in the case of optimal management and 23.36% in quasioptimal management. The total saving of energy resources (cooling water and the needed steam) amounts to 13.49% for optimal management and respectively 13.37% for quasioptimal management. Important is to noted that using the the system for heat integration leads to reduced used steam and cooling water. The system for optimal management requires special management device to reproduce the obtained optimal control law for control of the flow of cooling water for different intervals. Significantly simple law for the management of the flow of cooling water can be used for quasioptimal management, while the economic effect is similar. On behalf of that the quasioptimal management does not require special control devices and is feasible in practice.

6. CONCLUSION

As a result of the survey can be concluded that:

1. A mathematical formulation of the task for managing the processes in the system with heat integration is proposed.
2. The task for management is formulated in terms of mixed nonlinear mathematical programming with criterion for minimum cost of used energy from external sources
3. A mathematical formulation of the task for quasioptimal processes management in the system with heat integration is proposed.
4. The task is formulated in terms of NLP.

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