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Control system with the specific performance index for an evaporator

by

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Abstract: In some cases the classical performance indexes are not adequate for the performance evaluation of the concentration control systems. Therefore, the specific performance index is proposed in this paper. This index depends on the product of the product flow rate and some function of the deviation of the product concentration from the set point. In order to minimize this performance index the special control system is proposed. This special control system used to the forced circulation evaporator is studied using simulation techniques. The simulation results show that the system described in this paper produces the performance index less than classical control system.

Keywords: Performance index, concentration control, evaporator control system, simulation.

1. Introduction

In the control system design hierarchy for the chemical plants the inventory regulation is left to the end of the design procedure (see Kestenbaum and al., 1976, Stephanopoulos, 1984, Ponton and Laing, 1993). The control loops associated with product rate, overall conversion and product quality are considered as more important because they affect the economic performance of the plant. The goodness of the control loops for the product composition is evaluated on the basis of the "classical" performance indexes such as Integral Quadratic Performance Index or Integral Absolute Error. The goal of liquid level control in vessels is to provide outlet flow smoothing rather than tight level control. Simultaneously, the minimal and maximal levels are not exceeded. However, in some cases, the economic losses or the losses due to the harmful effect of the product on the environment (for ex. in the pH neutralization systems), depend on the product of the flow rate and some function of the regulation error of the product concentration. In order to evaluate the goodness of the control systems in such cases, the specific performance index has been proposed by Switalski (1983). This index has a form as follows:

$$J = \int_0^T V^*(t) f[\Delta c(t)] dt \tag{1}$$

where:
J - performance index,
t - time,
$V^*(t)$ - product flow rate,
$\Delta c(t)$ - deviation of the product concentration from set point.

The form of the f function may be different and depends on the process character. Using the capacity of the vessel it is possible to control $V^*(t)$ in order to minimize the performance index J. In this case the role of the level loop control is different from that in the classical system. The idea mentioned above may be used for the different plants such as evaporators, rectification columns, stirred tanks reactors, etc. The simulation results of the special control system for an evaporator are presented in this paper. These results showed that this special control system reduces the index J in comparison with the classical system.

2. The evaporator model

The concentration of dilute liquors by evaporating solvent from the feed stream is an important industrial process. The mathematical models of different types of evaporators are presented in the papers of Anderson and al. (1961), Newell and Fisher (1972), Newell and Lee (1989). The model of the "forced circulation evaporator" described by Newell and Lee (1989) is used in this paper. The simplified flow diagram of this plant is shown in Fig.1.

In this evaporator, feed is mixed with a recirculating liquor and is pumped into a vertical heat exchanger. The heat exchanger is heated with steam that condenses on the outside of the tube walls. The liquor boils in the exchanger and passes to a separation vessel. In this vessel liquid and vapour are separated. The liquid is recirculated with some being drawn off as product. According to Newell and Lee (1989) the mathematical model consists of the equations:

Process liquid mass balance:

$$\rho A \frac{dL2}{dt} = F1 - F4 - F2 \tag{2}$$

Where: ρ is the liquid density, A is the cross sectional area of the separator. The product ρA is assumed to be constant at 20 (kg/m). $F1$ is the feed flowrate in (kg/min), $F4$ is the vapour flowrate in (kg/min), $F2$ is the product flowrate in (kg/min), $L2$ is the level in separator in (m).

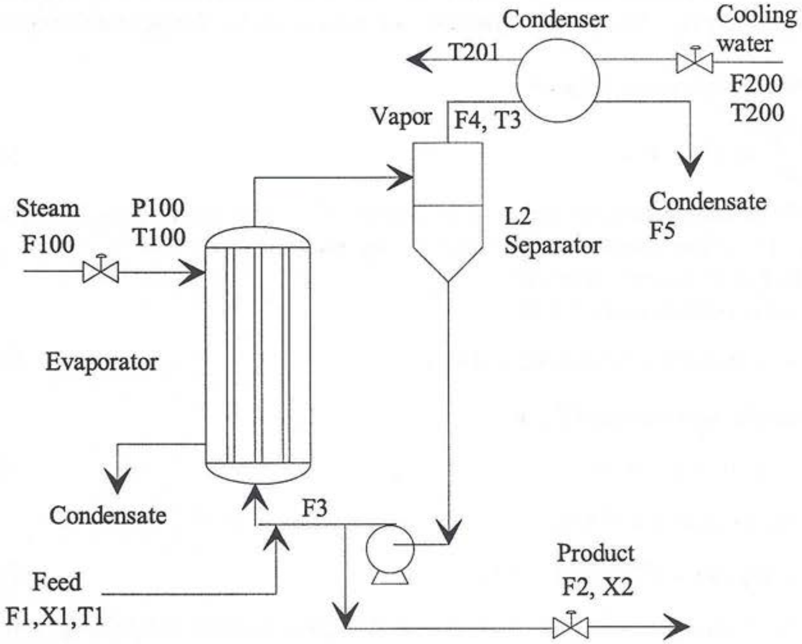

Figure 1. Flow diagram of the evaporator system.

Process liquid solute mass balance:

In the model originally developed by Newell and Lee the liquid hold-up in the evaporator is assumed to be constant. In our case this assumption is inadmissible because the changes of the level may be considerable. Therefore, the following form of this equation is proposed:

$$\frac{d}{dt}\left[(M0+\rho AL2)X2\right]=F1X1-F2X2 \tag{3}$$

where: $M0$ is the amount of liquid in the evaporator assumed to be equal to 20 kg, $X1$ is the feed composition in (%), $X2$ is the product composition in (%).

Although the modification is minor, the dynamic behaviour of the system changes significantly. The similar modification was made by Wang and Cameron (1994).

Process vapour mass balance:

$$C\frac{dP2}{dt}=F4-F5 \tag{4}$$

where: $P2$ is the operating pressure in (kPa), C is the conversion factor in (kg/kPa), $F5$ is the condensate flowrate in (kg/min).

Process liquid energy balance:

The liquid temperature $T2$ is:

$$T2=0.5616P2+0.3162X2+48.43 \tag{5}$$

The vapour temperature $T3$ is:

$$T3=0.507P2+55.0 \tag{6}$$

The vapour flowrate $F4$ is:

$$F4=(Q100-F1C_p(T2-T1))/\lambda \tag{7}$$

where C_p is the heat capacity of the liquor and is equal to 0.07 kW/K (kg/min).

λ is the latent heat of vaporization equal to 38.5 kW/K (kg/min)

Heater steam jacket:

Steam temperature $T100$ under saturated conditions is:

$$T100=0.1538P100+90 \tag{8}$$

The rate of heat transfer to the boiling process liquid is given by:

$$Q100=0.16(F1+F3)(T100-T2) \tag{9}$$

The steam flowrate is:

$$F100=Q100/\lambda_s \tag{10}$$

where λ_s is assumed constant at the value of 36.6 kW/(kg/min)

Condenser:

A cooling water energy balance:

$$Q200 = F200C_P(T201 - T200) \tag{11}$$

where $F200$ is the cooling water flowrate in (kg/min), $Q200$ is the condenser duty in (kW), $T200$ is the cooling water inlet temperature, $T201$ is the cooling water outlet temperature.

The heat transfer rate equation is:

$$Q200 = UA2(T3 - 0.5(T200 + T201)) \tag{12}$$

where overall heat transfer coefficient $UA2 = 6.84$ (kW/K)

The condensate flowrate is:

$$F5 = Q200/\lambda \tag{13}$$

where λ is the latent heat of vaporization of water equal to 38.5 kW/K (kg/min)

In these 12 equations there are 20 variables. The input variables are specified as follows:

3 manipulated variables - $F2$, $P100$, $F200$

5 disturbance variables - $F3$, $F1$, $X1$, $T1$, $T200$

3. The performance index and the control system structure

The performance index is assumed as follows:

$$J = \int_0^T F2f(X2 - X20)dt \tag{14}$$

where $X20$ is the required value of the product concentration.

In this paper the f function is assumed as follows:

$$f(X2 - X20) = 0 \text{ if abs } (X2 - X20) \leq \epsilon \tag{15}$$

$$f(X2 - X20) = 1 \text{ if abs } (X2 - X20) > \epsilon \tag{16}$$

For the normal operation of the evaporator, the control of the pressure $P2$, of the concentration $X2$ and the level $L2$ is required. The control problems of the pressure $P2$ and of the concentration $X2$ are solved by PID controllers. The manipulated variables are respectively: $P100$ and $F200$. For the level control loop the two input controller is proposed in order to minimize the performance index J. This controller takes advantage of the product accumulation in the separator vessel. The algorithm of the level regulator is described as follows:

$$F2 = F2\max \text{ if } L2 > L2\max \cup [\text{abs } (X2 - X20) \leq \delta \cap L2 > L2\min] \tag{17}$$

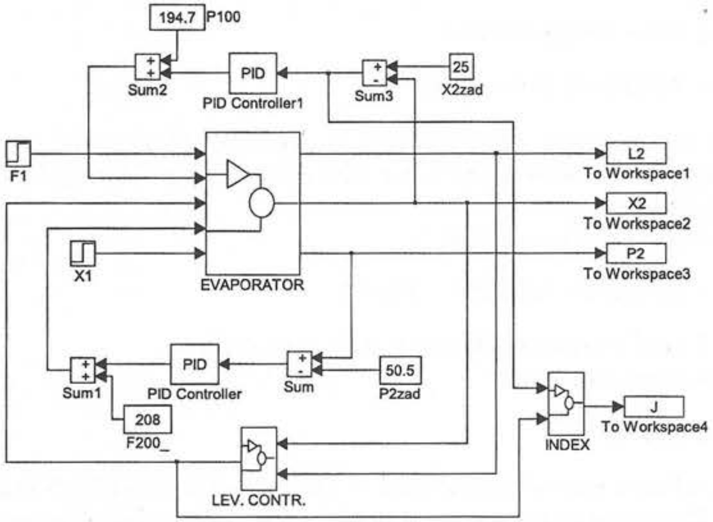

Figure 2. The structure of the evaporator control system.

$$F2 = 0 \text{ if } L2 < L2\min \cup [\text{abs}\,(X2 - X20) > \delta \cap L2 \leq L2\max] \tag{18}$$

The structure of the control system is presented in the form of SIMULINK block diagram (Fig. 2). The block EVAPORATOR represents the mathematical model of the evaporator, that is the equations (2) to (13). The block INDEX represents the equations (14) to (16). The block LEV.CONTR represents the equations (17) and (18).

4. Simulation results

The system with the controller described by the equations (17) and (18) has been compared with the classical system when the level was constant. Both systems have been tested for two disturbances: $F1$-feed solution flow rate and $X1$-feed solution concentration. The variables steady state values according to Newell and Lee (1989) are shown in Table 1. The other variables have the values: $L2\min = 1$ [m], $L2\max = 2$ [m], $\epsilon = 1$ [%], $T = 60$ [min], $\delta = \epsilon$. Fig. 3 shows the responses of the $X2$, $L2$, and J to step change in the disturbance variable $F1$ of 10%, that is from 10 to 11 [kg/min], for the classical and special control systems. The special system reduces the index J from 36 to 19 units.

The reduction of the performance index depends on the separator capacity, that is on the $L2\max$: it is shown in Fig. 4. The value of the index J depends also on the disturbance amplitude: it is shown in Fig. 5. When the amplitude

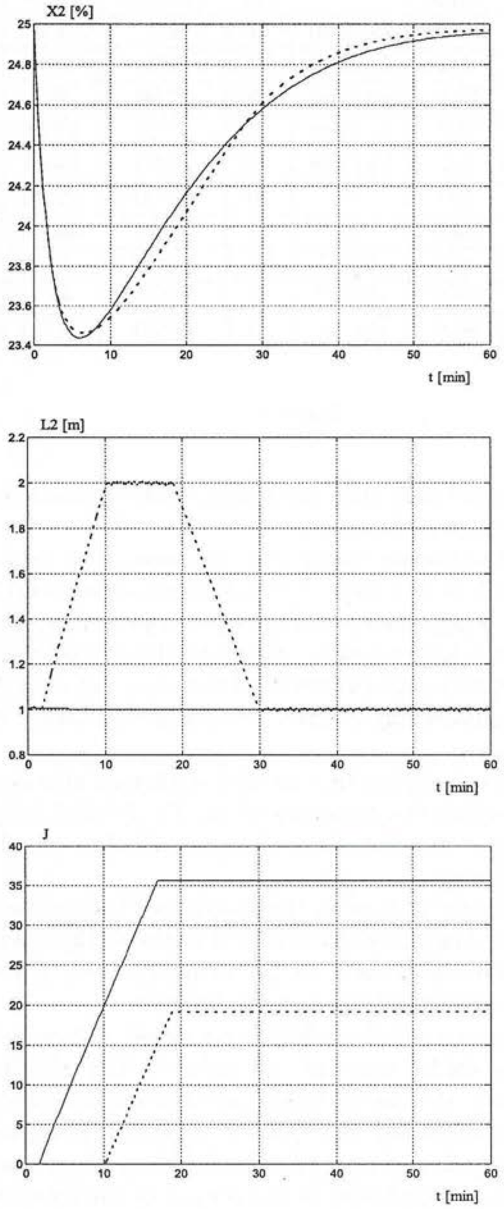

Figure 3. $X2$, $L2$ and J in the classical system (solid line) and in the special system (dashed line).

No	Variable	Value		No	Variable	Value	
1	F1	10.0	kg/min	11	L2	1.0	m
2	F2	2.0	kg/min	12	P2	50.5	kPa
3	F3	50.0	kg/min	13	F100	9.3	kg/min
4	F4	8.0	kg/min	14	T100	119.9	deg C
5	F5	8.0	kg/min	15	P100	194.7	kPa
6	X1	5.0	%	16	Q100	339.0	kW
7	X2	25.0	%	17	F200	208.0	kg/min
8	T1	40.0	deg C	18	T200	25.0	deg C
9	T2	84.6	deg C	19	T201	46.1	deg C
10	T3	80.6	deg C	20	Q200	307.9	kW

Table 1.

of the $F1$ step change increases then the index J also increases and the relative efficacy of the special system decreases.

Fig. 6 shows the responses of the $X2$, $L2$, and J to step change in the disturbance variable $X1$ from 5 [%] to 7 [%], for the classical and special control systems. If $L2\max = 3$ [m], the special system causes reduction of the index J from 40 to 8 units. It is interesting to note that the concentrations $X2$ in the classical and special systems are practically the same, although the "inertia" of the special system is considerably greater. The parameters of the PID controllers are the same in all cases.

The efficacy of the special system has been confirmed also for the sinusoidal disturbances. Fig. 7. shows the responses of the $X2$, $L2$ and J to the sinusoidal variations of the $F1$ flowrate. The disturbance amplitude is equal to 1 [kg/min], frequency $= 0.1$ [rad/min].

There is one parameter to tune in the special level controller. This is the δ value. However, for the function described by equations (15) and (16) the tuning is very simple. The minimal value of the performance index J is obtained when $\delta = \epsilon$. This is not true for other forms of the function f.

The main disadvantage of the solution presented above is that it causes violent changes of the outlet flowrate. In order to keep the level $L2$ on the value $L2\min$ or $L2\max$, the special level controller works in the sliding mode, so the outlet flowrate oscillates very quickly between F2max and zero. This solution may be difficult from technical point of view. Some smoothing of the outlet flowrate may be accomplished by the control of two overflows situated on two different levels $L2\min$ and $L2\max$. The outlet from the higher overflow is always open. The special controller opens or closes the outlet from the bottom overflow. The bottom overflow is open if:

$$\text{abs}\ (X2 - X20) < \epsilon \qquad (19)$$

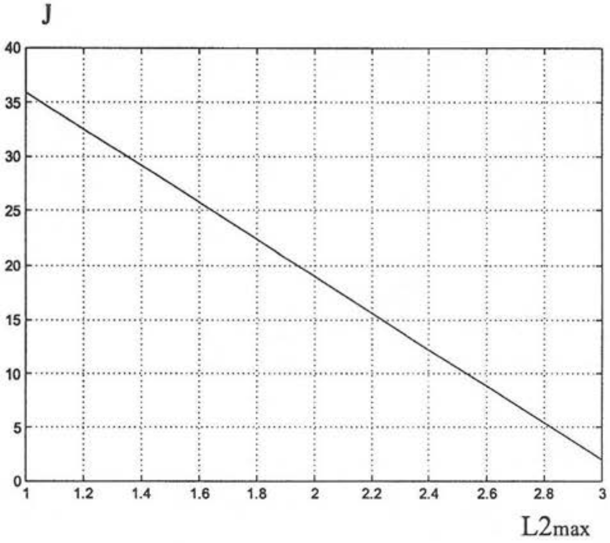

Figure 4. Index J as the function of the $L2\,\mathrm{max}$.

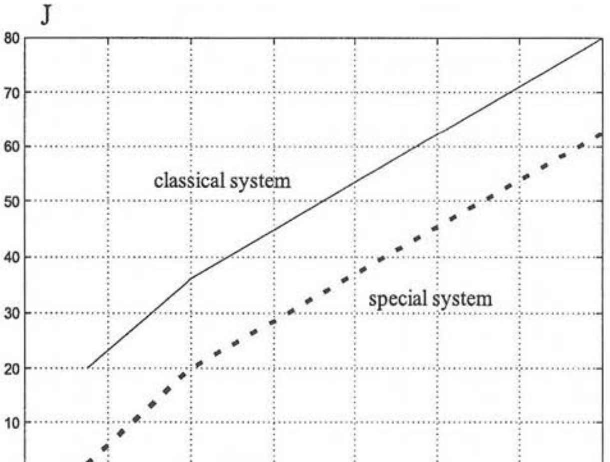

Figure 5. Index J as the function of the amplitude of the $F1$ step change.

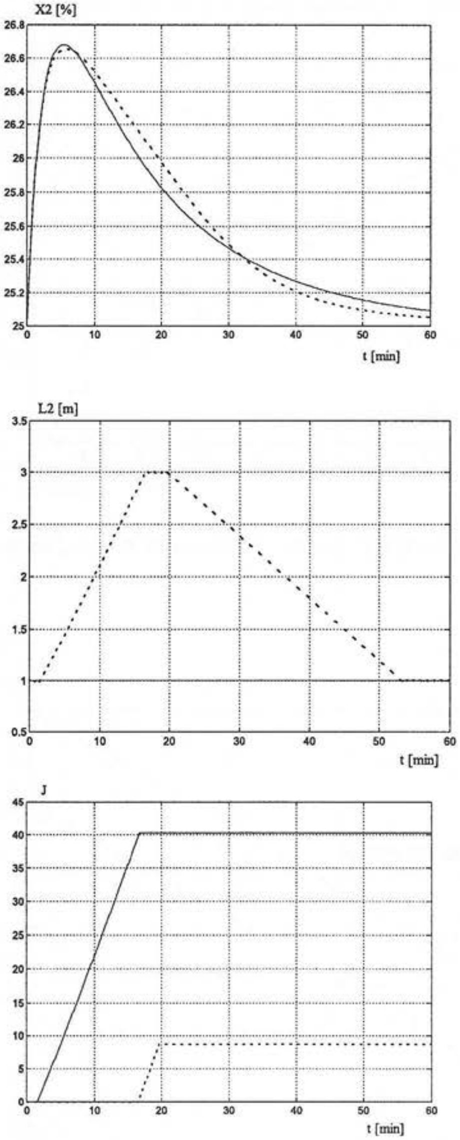

Figure 6. $X2$, $L2$ and J in the classical system (solid line) and in the special system (dashed line).

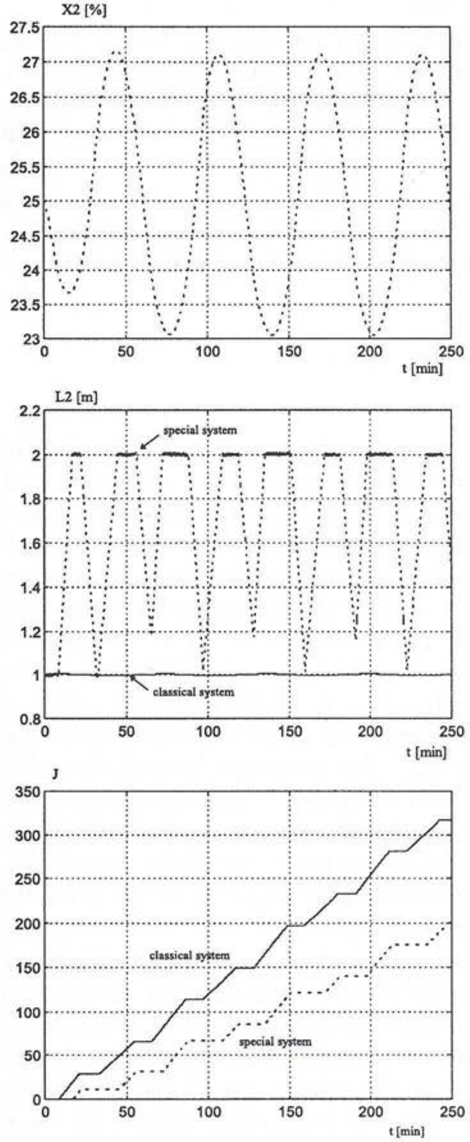

Figure 7. $X2$, $L2$ and J in the classical system (solid line) and in the special system (dashed line).

The simulated results for this case are presented in Figs. 8 and 9. The disturbance is the sinusoidal change of the $F1$ flowrate, with amplitude 1 [kg/min] and frequency 0.1 [rad/min]..

The changes of the flowrate $F2$ are still very violent but their frequency is less than in the previous case. The structure of the level controller is simpler because this controller has only one input, which is the concentration $X2$. The performance index has the identical value as in the system with controller described by the equations (17) and (18). The differences in the behaviour of the levels are small. The application of this solution is possible if the separator vessel is especially designed. However, the idea concerning the interaction between design and control is often and often recognised (see Luyben and Floudas, 1994).

5. Conclusions

The starting-point of this paper is the statement of the fact that in some concentration control systems the performance index should depend on the product flowrate and on some function of the concentration deviation. This is true especially for the processes providing the final product of the plant and for the processes which produce the product harmful for the environment. As an example of such type of the process the forced circulation evaporator is chosen. In this paper the specific performance index is an integral of the product of the flowrate and the absolute value of the concentration deviation. The special control system uses the capacity of the separator vessel to minimize this performance index. The role of the liquid level control is then different from that in the classical systems. The simulated results showed that the control system with the special level controller diminishes the performance index J in comparison with the classical system in which the level is constant. For the performance index assumed in this paper the parameters of the level controller do not depend on the amplitude and character of the disturbances. Switalski (1998a) shows that for another form of the index this does not hold.

The proposed solution has some disadvantages. Firstly, the special controller produces the violent changes of the outlet flowrate. Secondly, the vessel must to have the reserve of the capacity which may be used by the special controller. Finally, in case of the solution with two overflows the separator vessel must be especially designed. However, the author hopes that the concept of active using of the vessels' capacities may be successfully applied to the control of some technological plants.

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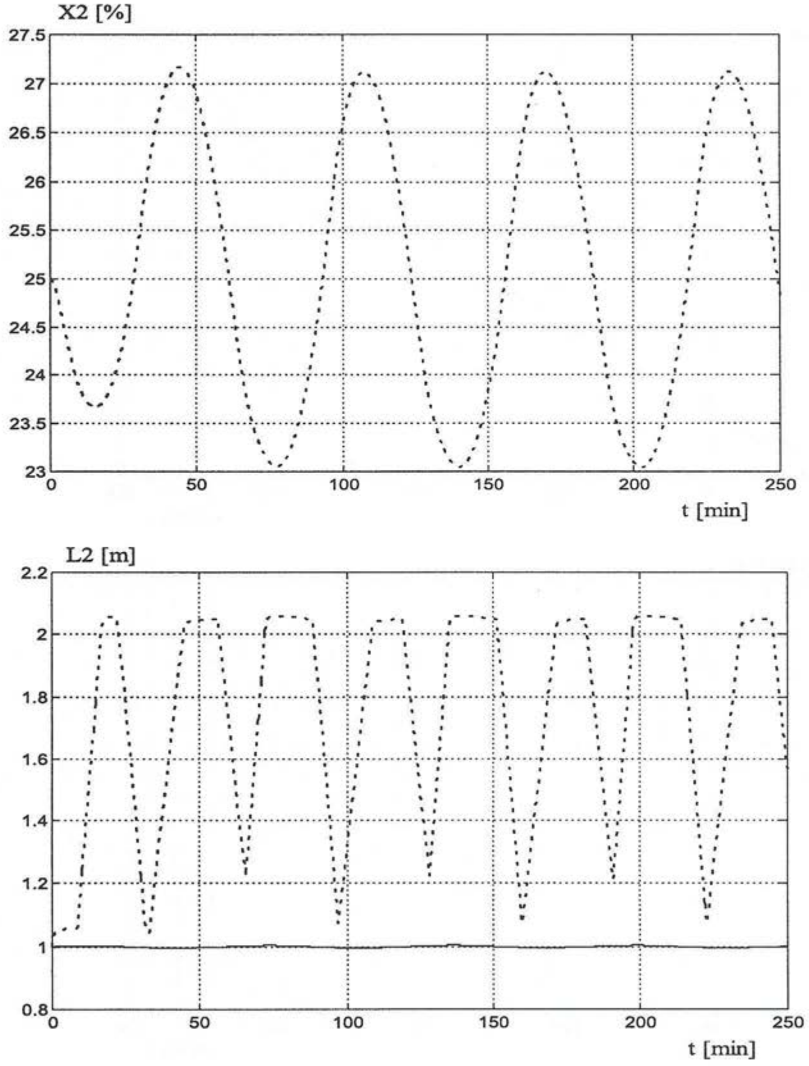

Figure 8. $X2$, $L2$ in the classical system (solid line) and in the special system (dashed line).

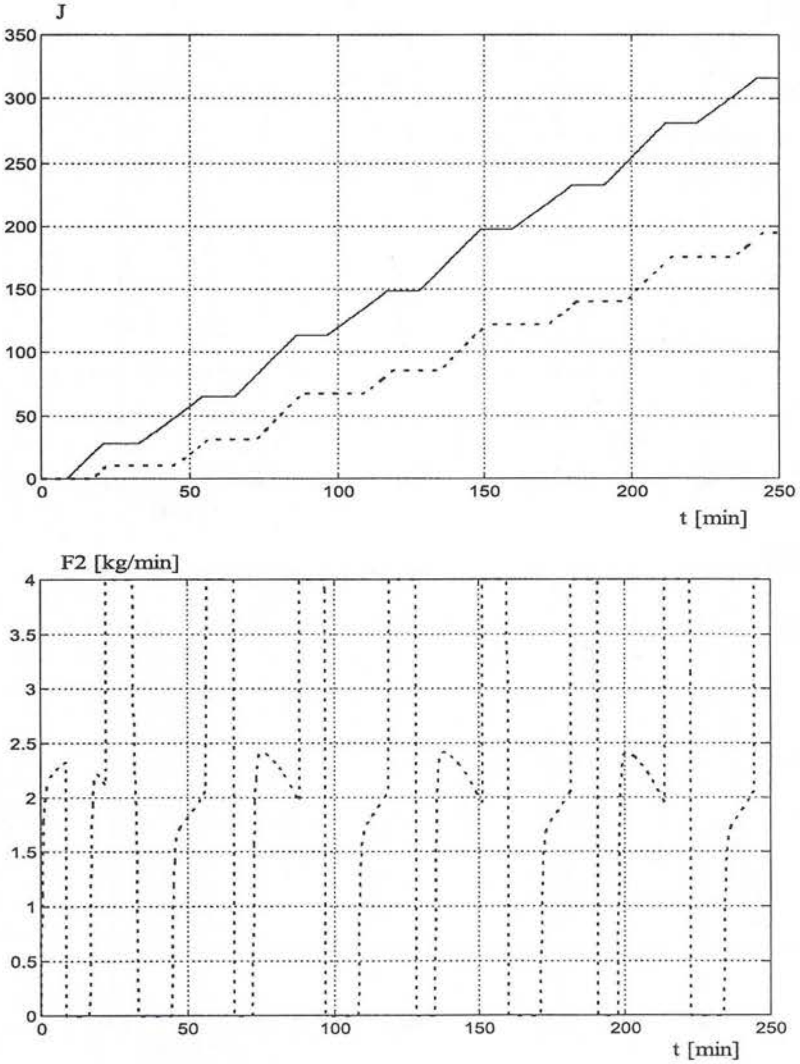

Figure 9. J and the outlet flowrate $F2$ in the classical system (solid line) and in the special system (dashed line).

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