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A NEW CONTROL ALGORITHM FOR CONCENTRATION CONTROL IN THREE EFFECT FALLING FILM EVAPORATORS[*]

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Abstract– Falling film evaporators have been given great attention due to their wide applications in industrial processes. In these processes, due to large time delay and disturbances the tight exact and proper control of product concentration is difficult. In this study, a nonlinear dynamic model has been considered for modeling and simulation of a three-effect falling film evaporator. The basic structure of the model is composed of heat and mass conservation equations coupled with thermodynamics as well as auxiliary correlations for prediction of physical properties. Also, a triple loop cascade control is proposed and tuned for control of this process. The proposed algorithm consists of three conventional loops. Results obtained from this proposed algorithm are compared with results of conventional PID control. It is shown that the regulatory and servo responses can be significantly improved by the proposed control algorithm.

Keywords– Falling film evaporator, nonlinear modeling, cascade control, regulatory control and servo control

1. INTRODUCTION

Evaporation is a key operation in industries, and among many types of evaporators, falling film evaporators are commonly used in industrial processes. Evaporators are used to concentrate solutions or to recover dissolved solids. Many types of evaporators are used in industry such as kettle reboiler, falling film evaporator, thermosiphon evaporator, short and long vertical tubes and etc. In falling film evaporators, liquid is distributed at the tops of individual tubes and flows down as a film inside them. Falling film evaporators have some advantages such as: no hydrostatic head, low pressure drop and excellent heat transfer. Since the contact time is short and separation of liquid and vapor is virtually complete, falling film evaporation is suitable for thermally sensitive materials. When condensable steam is used to evaporate water from an aqueous solution, the heat of condensation of higher temperature condensing steam is less than the heat of vaporization of lower temperature boiling water. Consequently, less than one kilogram of vapor is produced per one kilogram of consumed steam. Steam economy is defined as the ratio of vapor mass produced to steam mass consumed. The steam economy is a major parameter in the design and operation of evaporators. To reduce the required steam and increase the steam economy, a set of evaporators can be used. Increase of the steam economy is achieved by operating effects at different pressures and consequently at different boiling temperatures, so the vapor produced in one effect can be used in another effect. Due to the wide application of multi-effect falling film evaporators in industry, the study and analysis of this process is important. Food industries use multi effect evaporators in the syrup process, and the concentration of milk, fruit juice and tomato paste [1-3].

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Due to the effect of concentration rate on quality and energy consumption in the production stage, modeling and on-line control of this process is inevitable. Various research approaches have been considered in the field of evaporator modeling. Andre and Ritter investigated a laboratory two-effect evaporator system, dynamically [4]. They presented a simple and accurate mathematical model for this process. Winchester and Marsh studied a falling film evaporator in terms of controllability and concluded the weak controllability of the unit [5]. Haj Assad and Lampinen presented a mathematical model for falling film evaporation process [6]. It was shown that the interfacial shear stress has a considerable negative effect on the cooling rate.

Performance of various control algorithms have been studied on evaporators. Van Wijck et al. controlled a four-effect falling-film evaporator by multi variable supervisory control [7]. They showed that the multi variable supervisory control will enable industry to improve process efficiency. Tade and Le Page studied differential geometric nonlinear controller efficiency on an industrial evaporator system [8]. They showed that the performance of the nonlinear controller was better than PID controller for set point tracking and disturbance rejection. Kam and Tade studied nonlinear controller algorithm for the five-effect evaporator model [9]. Simulated results indicated that the multi-input multi-output globally linearizing control structure provides superior servo and regulatory control compared to PI controllers that are currently being used in the five-effect evaporator. Huub et al. used the conventional cascade control algorithm for multi effect evaporators [10]. They showed that the disturbance rejection properties can be significantly improved with cascade control strategy. Karimi et al. used inferential cascade control algorithm for multi-effect falling-film evaporator [11]. They proved that by using linear Kalman filter, the solid concentration of first effect can be significantly estimated. The estimated state was utilized in cascade control as the secondary measurement. Other modern control algorithms are applicable in this process such as the fuzzy controller algorithm [12]. Also, due to foaling in evaporators, the heat transfer coefficient changed and the robust controller for uncertain systems can be used in process control [13].

Nevertheless, single loop feedback controllers are still widely used in industry due to the complexity and high cost of advanced control systems. In this study, a three effect falling film evaporator is modelled and controlled. For modeling each effect, total mass balance, partial mass balance and energy balance as well as auxiliary correlations are considered. The design data of the three-effect falling-film evaporator in the Isfahan milk powder factory is used in the modeling stage.

2. PROCESS DESCRIPTION

A schematic of the three-effect falling-film evaporator is shown in Fig. 1. First, feed is pumped into pre-heaters to raise the temperature to the first effect temperature. After passing through pre-heaters, feed is pumped to the distribution plate which distributes the feed evenly to all evaporator tubes. The feed flows down inside the tubes and the flow forms a thin film along the wall. The live steam is injected into the shell side of the first effect and heat is transferred to the liquid film, so a percentage of solvent in the tubes is evaporated. The two phase flow, which consists of concentrated feed and vapor, is entered into the separator and then the liquid and vapor are separated. From the bottom of the separator, product is pumped toward the distribution plate of the next effect and vapor product exits from the top, and then enters into the shell side of the second effect. This process is repeated in the second and third effects. However, some of the exit vapor from the second separator is mixed with high pressure live steam and recycled to the shell side of the first effect. The leftover vapor from the second effect flows into the third effect.

In order to adjust the vacuum in the effects a total direct condenser is used. Cold water in the condenser and live steam flow rate are used as the manipulated variables to control the outlet product concentration in industry. In this study, the live steam flow rate is chosen as the manipulated variable due to faster response and direct effect on output concentration.

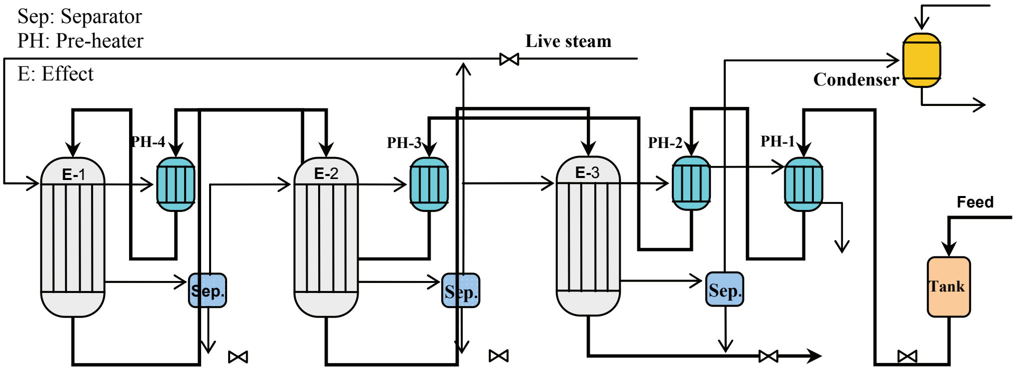

Fig. 1. Schematic of three effect falling-film evaporators

Calculated steady state values for temperature and concentration and design data of effects and pre-heaters are listed in Tables 1 and 2. These steady state values are used as initial values for dynamic modeling of the process.

Table 1. Parameters and steady state values of each effect

	Concentration (kg solid/kg milk)	Flow rate (kg/hr)	Overall heat transfer coefficient (W/m^{2}K)	Temperature (^{o}C)
Feed	0.0850	10000	-------	72
Effect-1	0.1335	6367.0	1735.0	72
Effect-2	0.2956	2875.5	1288.8	58
Effect-3	0.4800	1770.0	850.00	45

Table 2. Parameters and steady state values of pre-heaters

	Overall heat transfer coefficient (W/m^{2}K)	Temperature (^{o}C)
PH-1	2739.4	36.6
PH-2	1262.9	47.8
PH-3	2202.7	60.0
PH-4	2202.7	72.0

3. MATHEMATICAL MODELING

In this modeling, it is assumed that:
- The overall heat transfer coefficient between milk and steam is constant.
- It is considered that the liquid and vapor phase are at equilibrium condition.
- Liquid volume in effects is constant, thus milk holdup in each effect does not change.
- Vapor accumulation in effects is negligible.
- Heat transfer only occurs between milk and steam inside the shell and heat losses to environment are negligible.

Dynamic model of ith effect can be expressed as:

$$\frac{dm_i}{dt} = m_{L\,i-1} - m_{L\,i} - m_{V\,i} \tag{1}$$

$$\frac{d(C_i m_i)}{dt} = C_{i-1} m_{L\,\mathrm{i-1}} - C_i m_{L\,\mathrm{i}} \tag{2}$$

$$\frac{d(m_i H_i)}{dt} = m_{L\,\mathrm{i-1}} H_{L\,i-1} - m_{L\,i} H_{L\,i} - m_{V\,i} H_{V\,i} + Q_i \tag{3}$$

In equation 3, Q_i is the heat which exchanges between the vapor in the shell side and the solution in the tube side. The source of this energy in the first effect is the latent heat of the live steam and some of the vapor produced in the second effect.

$$Q_i = A_i U_i (T_{i-1} - T_i) = m_{V\,\mathrm{i-1}} (H_{V\,i-1} - H_{C\,\mathrm{i-1}}) \tag{4}$$

Experimental researches on falling film evaporators show that variation of mass accumulation with time is slower than variation of concentration and temperature with time [14]. Hence, it is possible to neglect variation of mass accumulation with time compared to concentration and temperature. For the approximation of the produced steam mass flow rate in ith effect and the milk enthalpy, the following empirical equations are used [15].

$$m_{V\,i} = K_{V\,i} m_{V\,\mathrm{i-1}} \tag{5}$$

$$H_L = (4186 - 3188.208C)\ T + 5.6484CT^{\,2} \tag{6}$$

$$H_{\mathrm{V}} = 1000(2503.1 + 1.7541T) \tag{7}$$

$$H_C = 4186T \tag{8}$$

Pre-heaters are used to increase the inlet milk temperature to boiling point temperature and there are four pre-heaters in this system. Due to no mass accumulation inside pre-heaters and constant milk concentration, the energy balance equation for the ith pre-heater is shown as follows.

$$\rho_F V_{P\,\mathrm{i}} \frac{dH_{F\,\mathrm{i}}}{dt} = m_F H_{F\,\mathrm{i-1}} - m_F H_{F\,\mathrm{i}} + Q_{PH\,\mathrm{i}} \tag{9}$$

In this modeling the sucking ratio (recycled vapor to live steam ratio) is assumed constant. The energy balance at mixing point can be computed by the following equation. It should be mentioned that m_{S-live} is the manipulated variable.

$$(m_{S-Live} + m'_{V2})H_S = m_{S-live} H_{S-Live} + m'_{V2} H_{V2} = Q_1 \tag{10}$$

4. CASCADE CONTROL

One of the very common control algorithms in process engineering is cascade control. This is a strategy that allows us to handle load changes more effectively. Generally, a cascade control structure is composed of two control loops, i.e. a secondary loop embedded within a primary loop. Load disturbances that affect the inner loop are reduced or counteracted before they extend to the primary outer loop. The secondary loop must have a faster response time than the outer loop [16]. A cascade control algorithm scheme is shown in Fig. 2.

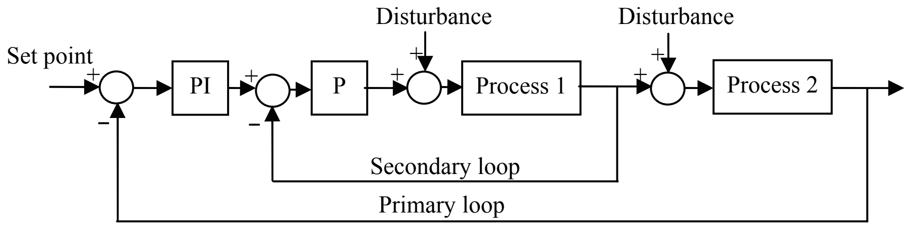

Fig. 2. Conventional cascade control

In chemical processes cascade control strategy can be used to improve the performance of control system particularly in the presence of disturbances on condition that the intermediate measurements are available.

5. TRIPLE LOOP CASCADE CONTROL

Researches show that factors such as feed concentration, feed temperature and temperature of cool water fed to the condenser can be considered as load disturbances. But, the disturbance is mainly due to the variation of feed concentration, and the effects of other disturbances on the concentration are insignificant [15]. In this work, we propose a triple loop cascade algorithm for control of the three-effect evaporator. The proposed triple cascade control and conventional cascade strategy are shown in Figs. 3 and 4. Proportional controllers (P) and proportional-integral controller (PI) are utilized in the inner loops and the outer loop in order to simplify and facilitate tuning. The estimated or measured outlet concentration of the first and second effect can be used as a secondary measurement for the inner loops in the proposed cascade control. In this scheme if the disturbance perturbs the output of the first effect, the deviation is significantly reduced by the first and second control loops through manipulation of live steam flow rate.

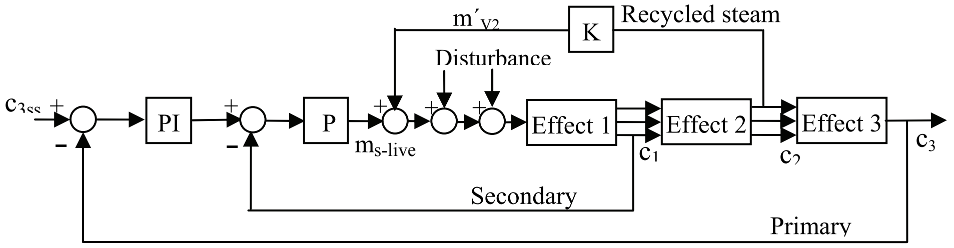

Fig. 3. Conventional cascade control

Subsequently, a part of the vapor from the second effect is recycled and mixed with the live steam and fed into the first effect. Whereas the sucking ratio is considered constant, the inlet vapor flow rate to the third effect will change, consequently.

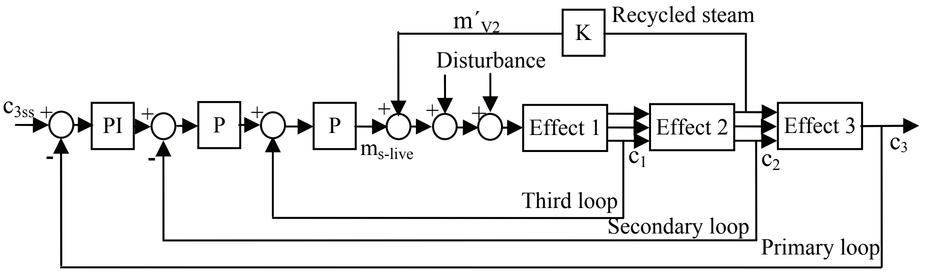

Fig. 4. Triple loop cascade control

The variation in the inlet vapor to the third effect leads to a variation in the concentration of the third effect. By using the third control loop, the output concentration from the third effect is regulated. Simulation results show that the performance of the proposed control is significantly faster and more accurate than the conventional feedback and cascade control.

Controller tuning- After the control system is installed, the controller settings must be adjusted until the control system performance is considered to be satisfactory. Different methods are proposed for controller tuning. In this study, the single loop PI controller is tuned by the Zeigler-Nichols method which is widely utilized in industry. Tuning of the cascade controller is carried out as follows:

1- In the first step, the secondary loop (proportional controller) is tuned by the Zeigler-Nichols method. In this step the primary loop is considered open.
2- Then, the primary loop is considered and its controller (PI controller) is tuned. In this step the secondary controller exists.

This procedure is efficient and simple for tuning the cascade controllers. But, if the inner loop is not faster than the outer loop, then the cascade will not offer any significant improvement in the process. Optimal parameters of the conventional cascade and the proposed control for the evaporators are presented in Tables 3 and 4.

Table 3. Optimal parameters of conventional cascade control

	K_C	τ_I	τ_D
Secondary loop	53.3		---
Primary loop	42	1.6	---

Table 4. Optimal parameters of proposed control

	K_C	τ_I	τ_D
Third loop	26.5	---	---
Secondary loop	25	---	---
Primary loop	21.4	1.44	---

6. RESULTS AND DISCUSSION

The mathematical model of the three effect falling film evaporator is solved using fourth order Runge-Kutta method, numerically. In order to show the effect of the input variables on the output concentration, the process response for a step change in the live steam mass flow, feed flow rate and feed concentration is presented in Fig. 5.

The proposed control algorithm, conventional feedback and cascade control strategy are performed on the process. The primary controlled variable is the outlet product concentration from the third effect and the manipulated variable is the live steam mass flow rate. The performance of the proposed method is compared with the conventional single loop and cascade control. Figure 6 shows the comparison between the performances of three control strategies for +20% changes in feed concentration. Variation of input variables are introduced after the process reaches a steady state condition.

It is shown that the overshoot is reduced from 11.25% to 4.8% for conventional feedback and cascade control respectively, and from 4.8% to 1.04% for conventional cascade control and proposed algorithm, respectively. Also, settling time is reduced from 505 to 287 seconds for the conventional feedback and proposed algorithm respectively. The overshoot is reduced about 91% by the proposed triple loop cascade control strategy.

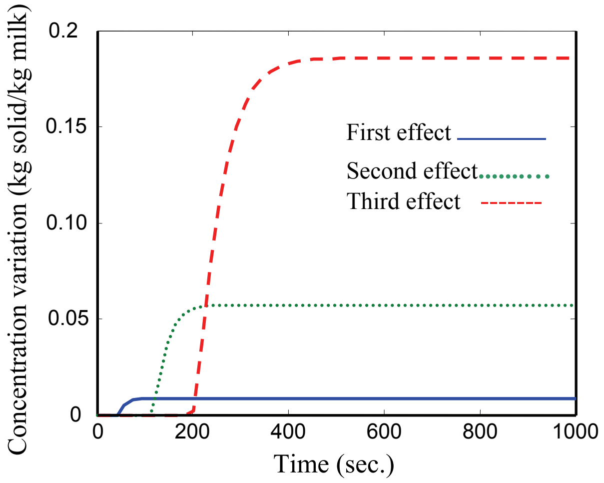

Fig. 5a. +10% step change in the live steam mass flow

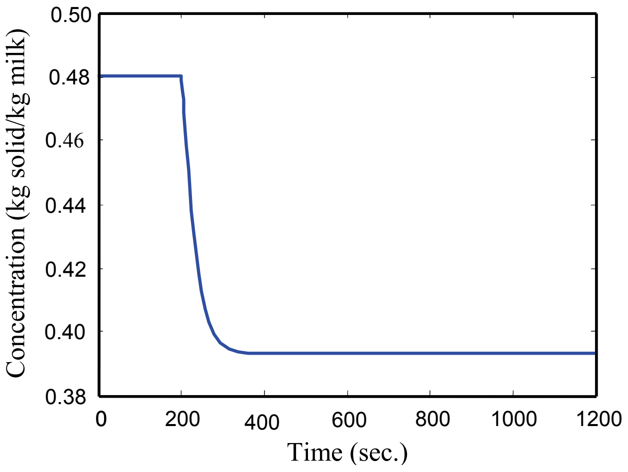

Fig. 5b. Outlet concentration from third effect for +5% step change in feed flow rate

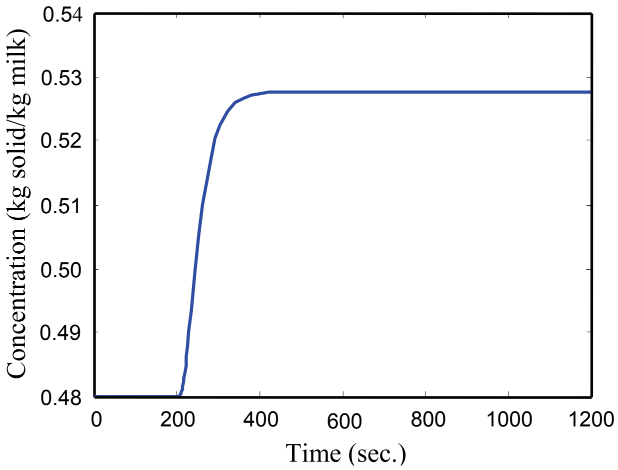

Fig. 5c. Outlet concentration from third effect for +10% step change in feed composition

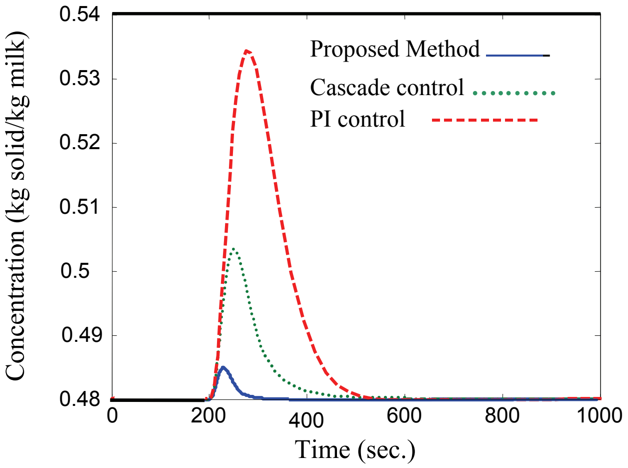

Fig. 6. Control response for +20% changes in feed concentration

In Table 5 characteristics of response for +20% changes in feed concentration are presented.

Table 5. Comparison of control loops results for +20% changes in feed concentration

	Overshoot	settling time (sec.)	IAE
Conventional controller	%11.25	505	5.43
Conventional cascade controller	% 4.8	445	1.72
Triple loop controller	%1.04	287	0.14

Figure 7 compares the output concentration of the third effect for -10% changes in the flow rate of feed for the three control algorithms. It is shown that the overshoot of the proposed control algorithm is lower than the conventional feedback and cascade control and it is more powerful in disturbance rejection. Figure 8 compares the output concentration of the third effect for +10 % changes in the set point for three control algorithms. This figure shows a rapid response and lower settling time for the proposed triple loop cascade control algorithm than the conventional feedback and cascade strategy.

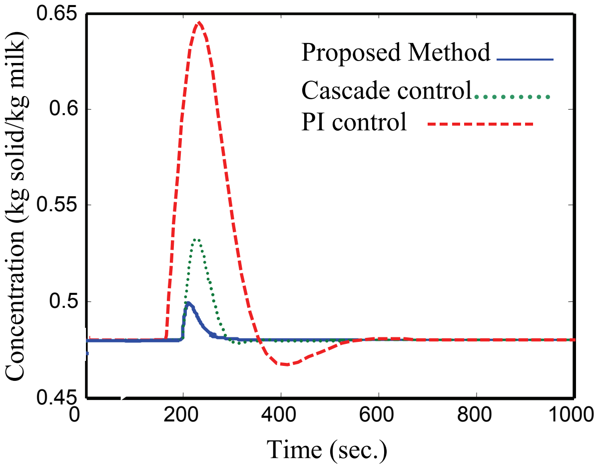

Fig. 7. Control response for -10% changes in feed flow rate

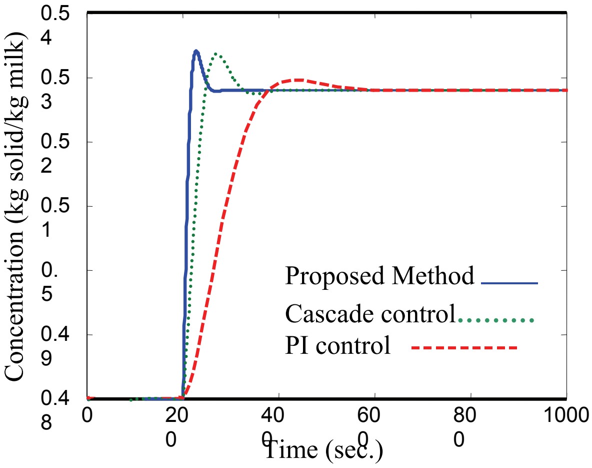

Fig. 8. Control response for +10% changes in set point

It is mentioned that the live steam flow rate is chosen as the manipulated variable for process control. Variation of the live steam flow rate in triple loop and conventional feedback control are shown in Fig. 9.

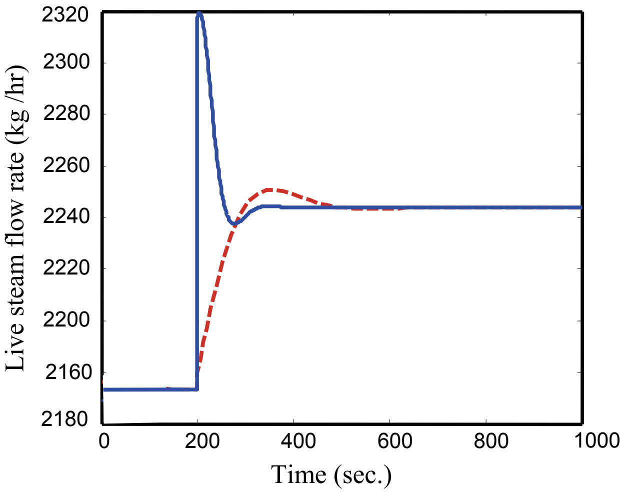

Fig. 9. Variation of the live steam flow rate

Process response characteristics for +10% changes in set point for conventional feedback, cascade and proposed controllers are compared in Table 6.

Table 6. Comparison of control response for +10% changes in set point

	IAE	Settling time (sec.)	Rise time (sec.)
Conventional controller	5.43	518	381
Conventional cascade controller	1.72	338	256
Triple loop controller	0.14	269	210

Results show that the response of the triple loop cascade controller is better than conventional feedback and cascade controller. The proposed control algorithm improved the control performance. Major benefits of the proposed triple loop cascade control for multi-effect falling-film evaporator are:

- decreasing the settling time and the rise time
- deceasing the overshoot
- decreasing the IAE

7. CONCLUSION

This study showed that the concentration control of the multi-effect falling film evaporator can be improved by use of the proposed algorithm. This proposed control algorithm is implemented on the three-effect falling film evaporator which is used in the milk industry. This control algorithm has been designed and tuned for disturbances rejection and set point tracking. The performance of this control algorithm is very satisfactory and is much better than the conventional single feedback and cascade control strategy. The proposed algorithm improves the characteristic of the response and control performance for servo and regulatory problems such as decreasing the settling time, overshoot and IAE.

NOMENCLATURE

A [m^2]	area
C	concentration
[kgsolid/kgmilk]	enthalpy
H [j/kg]	integral absolute of error
IAE	mass flow rate
m [kg]	heat flux
Q [j]	second
Sec.	temperature
T [^oC]	overall heat transfer coefficient
U [Wm^{-1}/K^{-1}]	volume
V [m^3]	density
ρ [kg/m^3]	

Subscripts

F	feed
i	ith effect
L	concentrated milk
Live	live steam
PH	pre-heater

s	first shell steam
V	Product vapor
w	cool water to condenser

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