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Nonlinear Modeling and Cascade Control Design for Multi Effect Falling Film Evaporators

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Abstract

Due to increasing application of multi effect falling film evaporators in food industry, the exact modeling of these processes is important. The aim of this paper is use ability of nonlinear modeling in determining falling film evaporator state variables. Because of large time delays and process disturbances, the tight exact control of product concentration is difficult. By using the nonlinear modeling, the control of three effect falling film evaporator with the use of cascade control algorithm is analyzed. This paper discusses the application and design of a cascade algorithm to control the product concentration in a milk powder three effect falling-film evaporator. It has been shown that the disturbance rejection properties can be significantly improved with cascade control while still maintaining the tracking properties.

Keywords: *Falling film evaporator, nonlinear modeling, cascade control, disturbance rejection*

Introduction

Evaporation is a key concentrate operation in dryer industry and falling film evaporators are common used ones among other types of evaporators in this field. Multi-effect falling film evaporators are used for concentration of solutions containing solid particles in food industry. Increasing of solid concentration is done by solution evaporation that in most of the cases is water. Because of wide application of multi-effect falling film evaporators in food industry, study and analysis model as a method of investigation of process operation receives high importance. Different studies have been conducted in the field of evaporator's modeling so far H.Andre and R. A. Ritter investigated a laboratory two effect evaporator systems in dynamic condition [1]. They presented a simple mathematical model as a modeling for this evaporator. According to complexity of equations in this modeling theorem results had a suitable accuracy. D. Grant Fisher and Robert Newell studied a two effect evaporating system. They converted a nonlinear model of tenth order to a linear model then used it for this system. Johnson presented an empirical model (black box model) for falling film evaporators and obtained parameters required in modeling experimentally [2]. In this model vapor phase variations were not considered with time and assumed that heat transfer from shell to tubes is independent of time. Manczack purposed

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an analytic model which predicted dynamic condition of one effect and multi effect evaporation operation [2]. Zavorka et al presented an overall model for evaporating operation of sugar solution [2]. In this model, a correlation for measuring value of total heat transfer coefficient with respect to sugar solution concentration and falling film liquid level inside tubes was presented [3]. In this system, milk was assumed as the feed and the target was production of dried milk. Quaak and Gerritsen performed a variety of activities in the course of dynamic modeling of falling film multi effect evaporators [4]. Quaak et al designed pilot plant of multi effect falling film evaporator in laboratory and studied the dynamic of process. Product solution solid concentration of evaporators influenced the conversion process of evaporated solution to dry powder hence control of product concentration is very important. For increasing of dry powder quality, disturbance bands which influence the process must be identified and eliminate them quickly, so control algorithm with capability of eliminating disturbance requires desired operation of control system.

Product concentration has the most influence from disturbances resulting of feed concentration and use of simple feedback controller in process. Winchester and Marsh studied a falling film evaporator as controllability point of view and the result was lack of controllability of that unit [3]. This result was obtained by Postlethwaite and Skogestad in past [5]. So it was not possible to identify considerable domain of disturbances. In continuation of this research it was demonstrated that main reason of no identifying precise domain disturbances in multi effect falling film evaporators had large time delay in this process. In recent years, in the field of control system design for falling film evaporators there have been so much activities and researches have used advanced control algorithms. For example Tade and Lepage studied nonlinear control algorithms [6]. Quaak, Van Haren and Van Wijck studied multi variable control algorithm for evaporators [7]. Lahtinen used fuzzy controller [8]. Lozano and Elastondo used adaptive controllers in their researches [9]. In the recent years, using of cascade control loops for multi effect evaporators has been studied by Marsh, H. C. Bakker, Paramaloingam and Hong Chen [10]. However, one loop feedback controllers still are used (because of complexity, maintenance cost and high price of improved control loops).

Process Description

For concentration of solutions are sensitive to high temperature like drug and food materials in order to sustain their drug or nutritional value, evaporation process must be done in the possible short time [11]. This work usually is done in multi effect falling film evaporators. Falling film evaporators unit is consisted of a certain number of evaporator, a condenser, steam thermo compressor, vacuum pumps, transitional pumps, separators and preheaters. Figure (1) shows a simple scheme of three effect falling film evaporator instruments. High heat transfer coefficient in low temperature is an advantage of this kind of evaporators. Process time is usually low (2-100 seconds) and hence, for temperature sensitive materials is quietly suitable. Because of the evaporation takes place on film interfacial surface, lower sediment appear in system.

In the cases that feed solution is sensitive to high temperature, vacuum (by vacuum pump or condenser) is used for reducing boiling temperature. Heating agent is steam which its property is determined base on concentrated solution and evaporation pressure.

In this paper, studied process is milk powder three effect falling film evaporator. In this process, initially milk is heated in first preheater by vapor which is exited from third effect separator and then is heated in second, third and fourth preheaters respectively by steam of third, second and first effect shells, and feed temperature reaches to suitable boiling temperature. Then feed is pumped to first effect evaporator and is distributed on evaporator tubes via feed dispenser. This feed moves in to evaporator tubes as a thin film and is transferred down wards. Required heat for evaporation is provided by low pressure steam in shell of first-effect. Mixture of steam and concentrated liquid in separator is separated via centrifugal force and steam is transferred to second effect shell and feed in transferred in to second effect tubes.

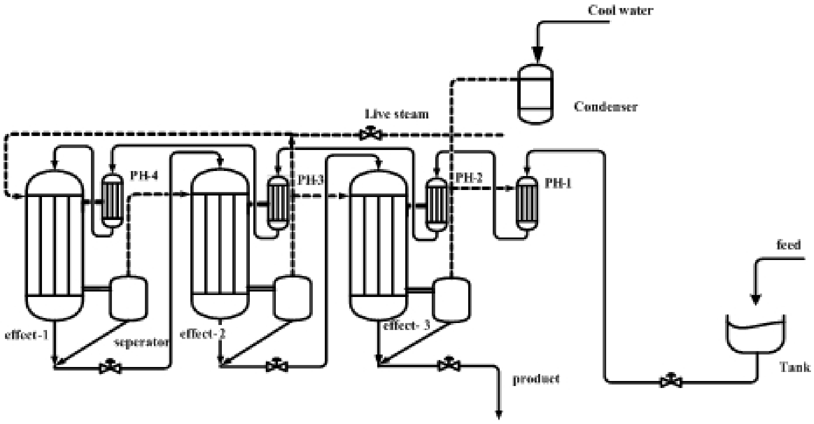

Figure 1. Schematic diagram of three effect falling-film evaporator

The same process is repeated for second and third effects. The part of second effect vapor is sucked by thermo compressor then is converted to low-pressure steam to be used in first effect. High pressure live steam is used to first effect shell for concentrating solution and steam supply required for fourth preheater. Steam inputs to second effect shell is used for concentrating solution and steam supply required for third preheater. Steam inputs to third effect shell for concentrating solution, supply steam required for second preheater and thermo compressor. Also product vapor in third effect is used for supplying steam required for fourth preheater and residual steam is liquefied by a barometric condenser that installed at the end of evaporation unit. The steady state values of three effect falling film evaporator and preheaters parameters listed in Tables (1) and (2).

Table 1. Steady state values of the three effect evaporator parameters

	Concentration (kgsolid/kgmilk)	Flow rate (kg/hr)	Heat transfer coefficient (W/m^{2}C)	Temperature (^{o}C)
Feed	0.0850	10000		72
Effect1	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. Steady state values of the four preheaters parameters.

	Heat transfer coefficient (W/m^2C)	Temperature (^oC)
PH-1	2739.4	36.6
PH-2	1262.9	47.8
PH-3	2202.7	60.0
PH-4	2202.7	72.0

Nonlinear modeling

Dynamic modeling of milk powder three-effect falling film evaporator

Dynamic modeling of milk powder three effect falling film evaporator consists of two main parts:

1- Dynamic modeling of three effect evaporator.
2- Dynamic modeling of four stages preheater.

Some assumptions are applied to dynamic modeling of milk powder three effect falling film
evaporator is described below:

1- Mass accumulation is occurred in evaporator separator part and only in liquid phase.
2- Energy accumulation is considered as a liquid volume accumulation in separator.
3- Total heat transfer coefficient between milk (liquid and vapor) inside tubes and steam inside shell a long evaporator tubes is assumed constant.
4- Milk liquid and vapor is considered in phase equilibrium condition.
5- Vapor produced in tubes and separator is transferred to next effect completely and there was no vapor accumulation inside evaporators.
6- Mass accumulation inside evaporator shell is assumed negligible.
7- Vapor produced inside evaporator tubes is without liquid milk or solid particles.
8- Temperature of produced vapor is assumed constant inside tubes in transfer to next evaporator shell.
9- Heat transfer only occurs between milk and steam inside shell and heat transfer to environment is negligible.
10- Liquid is distributed in top of tubes uniformly.
11- There was no mass accumulation inside preheaters.

Dynamic equation and experimental relations of three effect falling film evaporator

For each effect of evaporation process, a total mass equilibrium, a partial mass equilibrium and two energy balances is considered. Equations (1) - (4) present nonlinear dynamic model of ith effect of three effect falling film evaporator. State variables depended to time are total mass accumulation, component mass concentration and temperature.

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

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

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

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

Energy accumulation is legible inside falling film evaporator shell, therefore as shown in equation (4); dynamic condition is not considered in evaporator shell side. Experimental works and conducted researches in the field of falling film evaporators show that variation of mass accumulation with time compared to concentration and temperature variation with time is slower [12]. Hence it is possible to negligible variation of mass accumulation with time compared to concentration and temperature and consider amount of accumulation as a constant value ($dm_i/dt = 0$). For approximation of produced steam mass flow in ith effect, the experimental relationship in equation (5) is used [2].

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

Milk enthalpy is depended to temperature and concentration and for compute its value the experimental equation (6) is used.

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

Produced steam enthalpy and condensate steam enthalpy in each effect can be calculated by steam thermodynamic tables or linear equations (7) and (8).

$$H_V = 1000 \times (2503.1 + 1.7541 \times T) \tag{7}$$

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

In equation (3), enthalpy variation with time cab be extended as a function of concentration and temperature and replaced in equation (9).

$$\frac{dH}{dt} = \frac{\partial H}{\partial T} \times \frac{dT}{dt} + \frac{\partial H}{\partial C} \times \frac{dC}{dt} \tag{9}$$

In equation (9) $\frac{\partial H}{\partial T}, \frac{\partial H}{\partial C}$ can be replaced by experimental relations. Since heat transfer coefficient changes intensively with input condition changes, therefore given energy value to milk via shell is considered equal to steam enthalpy change inside shell and it is assumed that total steam inside shell is condensate (4). Above assumptions in all effect of falling film evaporator are valid.

Preheaters are used to increase milk temperature to boiling point temperature and contain four stages that are designed inside evaporators in reverse milk movement direction. Steam inside evaporator shell is used to heat milk and it is assumed that transfer heat value to preheater is such that does not convert milk in to two phase condition. respective relations to preheaters are identical and with the assumption of mass accumulation lack inside preheater and not changing milk concentration, the only applicable equation for preheaters is energy equilibrium in dynamic condition which respective equation of effect i is shown in the following.

$$\rho_F V_{P\,i} \frac{dH_{F\,i}}{dt} = m_F H_{F\,i-1} - m_F H_{F\,i} + Q_{PH\,i} \tag{10}$$

As mentioned above, consumed steam value in preheaters is determined according to a coefficient of steam value inside shell. Its accurate value determination is possible according to experimental data. Enthalpy variation with time can be specified according to temperature variation versus time and since concentration in preheaters is assumed constant, enthalpy variation relation is described as equation (11).

$$\frac{dH}{dt} = \frac{\partial H}{\partial T} \times \frac{dT}{dt} \tag{11}$$

Parameter $\frac{\partial H}{\partial T}$ can be calculated by experimental relations which this was explained in above. Because of lack of phase change inside preheaters, milk density is assumed constant. Steam thermo compressor mixed some of produced steam in the second effect but sucking in steam path of new input to first effect by making vacuum with new steam and then transfers it to first effect evaporator shell. Temperature and mass flow rate of live steam must be at a level that after mixing by second effect produced vapor required steam with suitable temperature can be prepared for first effect. By increasing live steam mass flow rate, the produced vacuum is more and as a result sucking ratio also increase. In this modeling sucking ratio is assumed constant and mixing of live steam and sucked steam from second effect is a fast isotropic process and it is energy balance can be computed by following equation.

$$(m_{S-Live} + m'_{V2}) \times H_S = m_{S-live} \times H_{S-Live} + m'_{V2} \times H_{V2} \tag{12}$$

Control of milk powder three effect falling film evaporator

In present years, simple feedback control algorithms are used widely in most chemical process [13]. One of the main disadvantages in simple feedback control algorithms, common used in industry is delayed reflux of manipulated variables. it is so that at the time of accuracy of disturbance in process, manipulated variables perform a suitable reflux when controllable variable exits desired domain of set point which this causes large time delay in control system. So using of simple feedback control loops where investigated for processes with large time delay or large process time constant. These algorithms where used almost merged in simple feedback control loops. These algorithms eliminate disturbances effect properly. For use feedback controllers, accurate disturbance measurement is needed and also purposed model for process must have high precision which this cause limitation in use of feedback control algorithms.

Cascade control of three effect falling film evaporator

Researches show that factors like feed concentration, feed temperature and temperature of cool water to condenser can exist some disturbances in evaporation process [3]. Feed temperature and cool water temperature do not influence on process control sensitively, while feed concentration can expel product milk concentration from desirable domain and influences control system. Use of second measurable variable and a simple second feedback control loop can interred disturbances in process identify faster that controllable variable in away that it is not necessary to measure disturbance value. Use of such algorithm operates quicker and more stable than simple feedback control loop. A cascade control algorithm is shown in Figure (2). As it is shown in Figure (2), internal loop controller output is specified as a desirable value of second variable.

Because of large delay time and present disturbances in process desirable and precise control of present solid value in product solution is difficult in falling film evaporators [10]. So use of single feedback controller is not sufficient to study this case. In present study cascade control algorithm is use to control product concentration. In following it is shown that, applied disturbances to process cab be rejected by a cascade control loop in away that output product concentration of third effect at a desirable value. Results obtained from cascade control algorithm are compared to the ones obtained from simple feedback control algorithm. In this research, first effect product concentration value is chosen as second measurable variable and third effect product concentration value is chosen as primary measurable variable. Live steam mass flow to thermo compressor is chosen as manipulated variable in two algorithms.

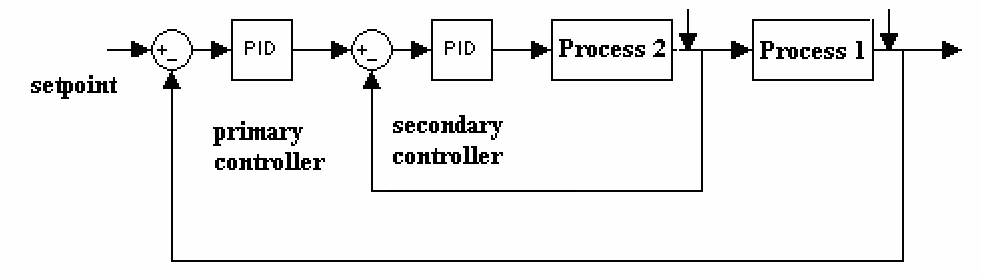

Figure 2. Cascade control algorithm

Tuning of cascade control loops

The implication of this is that the usual tuning technique for cascade control: tune the inner loop first and then tune the outer loop with the inner loop fixed can not be adopted, verbatim, in this case. Inner loop controller is P and with the inner loop controller tuned, the outer loop can be tuned to give good disturbance rejection and tracking performance. A PI controller is needed to achieve both of these tasks. The integral time is chosen to have phase lead before the phase cross over frequency and the proportional constant is selected to achieve the best compromise between the disturbance rejecttion and noise suppression bandwidths.

For a cascade control system to function properly, the response of the secondary control loop should be faster than the primary loop [14]. The secondary controller is normally a P or PI controller, depending upon the amount of offset that would occur with proportional-only control. Note that small offsets in the secondary loop can be tolerated since they will be compensated for by the primary loop. Derivative action is rarely used in the secondary loop. The primary controller is usually a PI and PID controller [15, 16].

First the inner loop frequently response for a set point change is calculated and a suitable value of secondary proportional parameter is determined. The offset is checked to determine if PI control is required. After secondary proportional parameter is specified, the outer loop frequently response can be calculated, as in conventional feedback controller design. For the design of primary controller we should consider the close loop transfer function for set point changes as well as the ones for load changes [17]. The design objective in these last two cases is to reject disturbances; we want load changes to be as small as possible for all frequencies. A resonant peak should appear in the amplitude ratio plot, and the controller should be adjusted to minimize this peak and force it to occur at as high a frequently as possible. Generally, cascade control is superior to conventional control in this regard, and also provides superior time domain responses [14, 17].

When a cascade control system is tuned after installation, the secondary controller should be tuned first (for set point changes) with the primary controller in the manual mode. Then the primary controller is transferred to automatic and it is tuned. The on line tuning techniques can be used for each control loop. If the secondary controller is retuned for some reason, usually the primary controller must also be retuned. When a cascade control system is transferred from the manual to the automatic mode, the secondary controller should be transferred before the primary controller. The order is reserved when transferring both loops from automatic to the manual mode.

Results

To solve differential equations result from milk powder three effect falling film evaporator and preheaters dynamic model numerical method as fourth order Runge-Kutta is used. For programming this process dynamic model the MATLAB 7.0.4 software was used and for design control algorithms the SIMULINK software was used.

Dynamic modeling results of milk powder three effect falling film evaporator

For study dynamic condition of three effect falling film evaporator, influence of variation of live steam mass flow rate to thermo compressor on product milk concentration and temperature of each effect was studied. As shown in Figures (3) and (4) product milk concentration and temperature are increased by increasing live steam mass flow rate. As it is observed from concentration and temperature diagrams third effect compared with first and second effects reaches to new steady state condition with a more time delay. Third effect is connected to final condenser hence while condenser is controlled by cool water mass flow rate, influence ability of third effect decreases with respect to input variations.

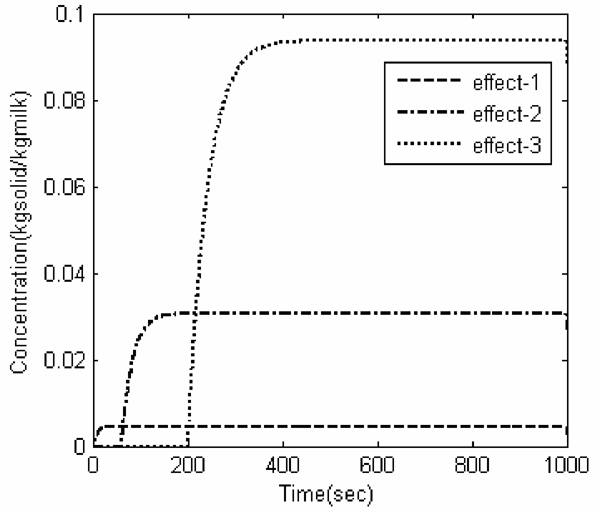

Figure .3 Dynamic response of product milk concentration to live steam mass flow rate. (2176 to 2300 kg/hr)

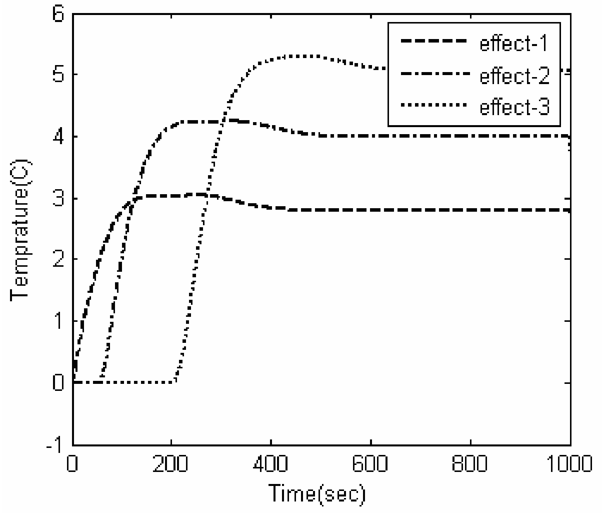

Figure 4. Dynamic response of evaporator temperature to live steam mass flow rate. (2176 to 2300 kg/hr)

In Figure (5) shows the influence of live steam mass flow rate change on preheaters output milk temperature. Because of present delay time in second and third effects of evaporation process, preheaters reach to uniform condition with more delay time compare to second and third effects of evaporation process. Therefore, this factor (large delay time) can influence the control operation of such processes.

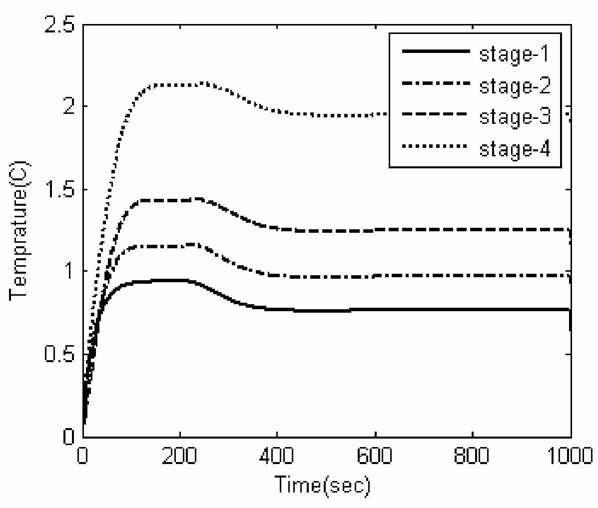

Figure 5. Dynamic response of preheater temperature to live steam mass flow rate. (2176 to 2300 kg/hr)

Feed flow rate is one of the main causes in existing of disturbances in evaporation process. It is shown in Figures (6) and (7), output milk concentration of each effect and evaporator temperature decrease by feed flow rate increase. Produced steam mass flow rate stays constant by increasing feed flow rate and as a result milk concentration decreases. Temperature variation in third effect occurs with a more delay time with respect to that of first and second effects, but temperature decrease is less than first and second effects.

The effect of feed flow rate increase on output temperature of preheaters is shown in Figure (8). Process heat transfer is constant and consequently by increasing feed flow rate to preheaters, output temperature of each effect decreases.

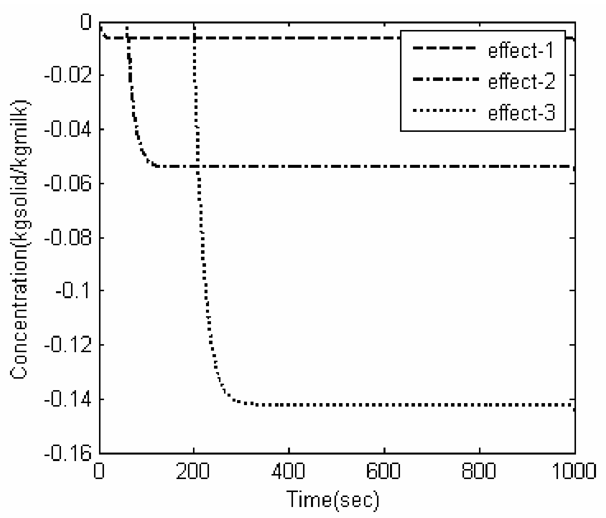

Figure 6. Dynamic response of product milk concentration to feed flow rate. (10000 to 11000 kg/hr)

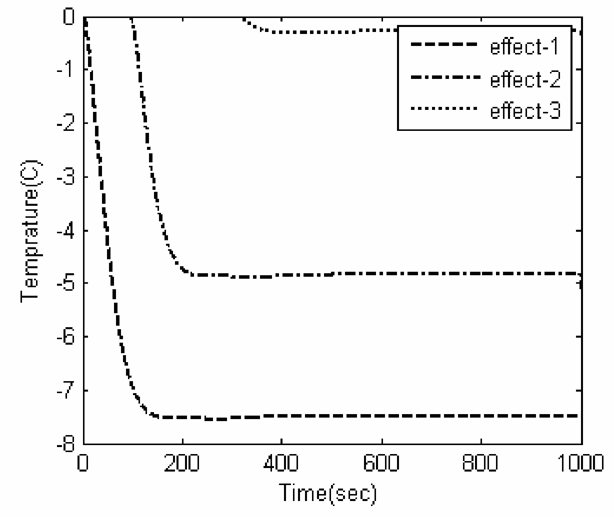

Figure 7. Dynamic response of evaporator temperature to feed flow rate. (10000 to 11000 kg/hr)

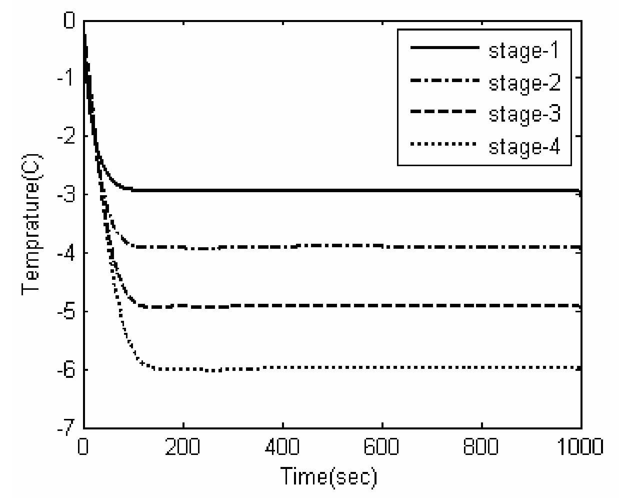

Figure 8. Dynamic response of preheater temperature to feed flow rate. (10000 to 11000 kg/hr)

Cascade control algorithm results for milk powder three effect falling film evaporator

Variations of product milk concentration of third-effect of milk powder evaporator unit are compared in Figure (9) and (10) in a closed loop system in two cases of cascade controller and simple feedback controller. The proportional controller and a proportional-integral controller were used in cascade control loop. In simple feedback control loop, the proportional -integral controller was used .effect of desirable value increase on product milk concentration was studied. Desirable value increased 8 percent. As it is shown in Figure (9) when using cascade controller, product milk concentration reaches closer to new desirable value and steady state quirkier than the case of simple feedback control. In a process that a cascade control algorithm is used and overshoot is observed in initial time but it is negligible. The effect of feed concentration on product milk concentration was studied. Feed concentration was increased 18 percent. As it is shown in Figure (10) while using cascade controller, product milk concentration eliminates disturbance effect faster than the case of simple feedback controller.

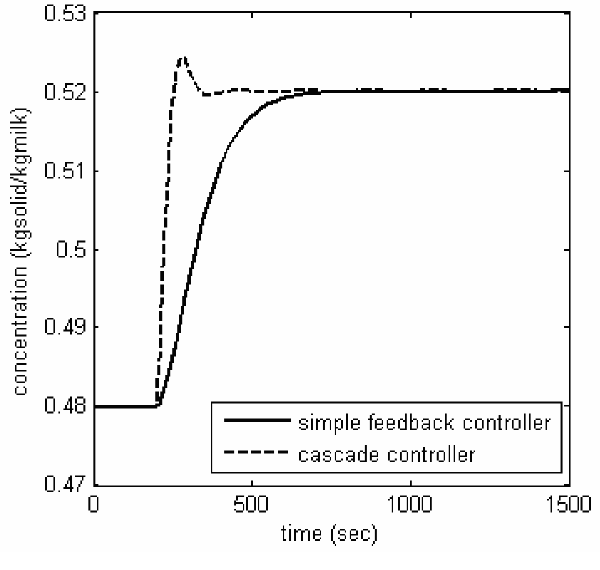

Figure 9. Response of concentration control loop to set point change. (0.48 to 0.52 kgsolid/kgmilk)

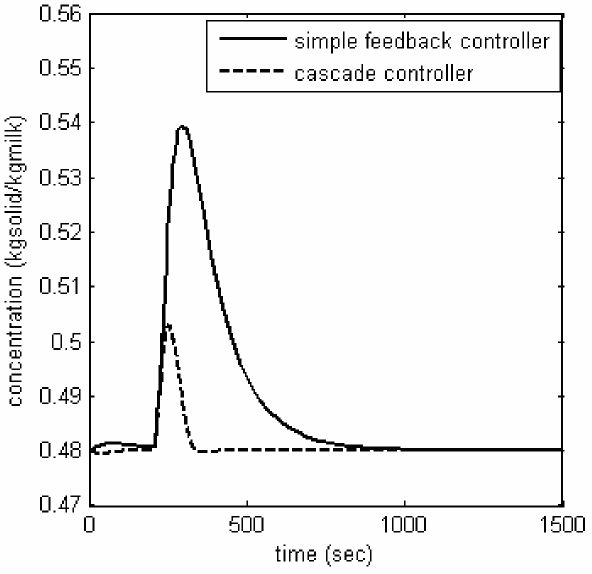

Figure 10. Response of concentration control loop to feed concentration disturbance. (0.085 to 0.1 kgsolid/ kgmilk)

The performance of manipulated variables in cascade control and simple feedback control are compared in Figure (11). Results show that in tow cases, the manipulated variable (Live steam flow rate) acts faster than simple feedback control.

In a process which a cascade control algorithm is used, the small overshoot is seen in initial time but its value compared to simple feedback control case is negligible. In a case that a simple feedback control algorithms was used, disturbance effect disappears further and disturbances exist in process have a very unsuitable effect on product milk concentration.

For analysis the performance of cascade control we use ISE method for setpoint tracking and load rejection. Results are listed in Table (3) and compared with simple feedback control.

Table 3. ISE values of simple loop and cascade loop.

ISE	Setpoint tracking	Load rejection
Simple loop	0.1	0.4
Cascade loop	0.05	0.01

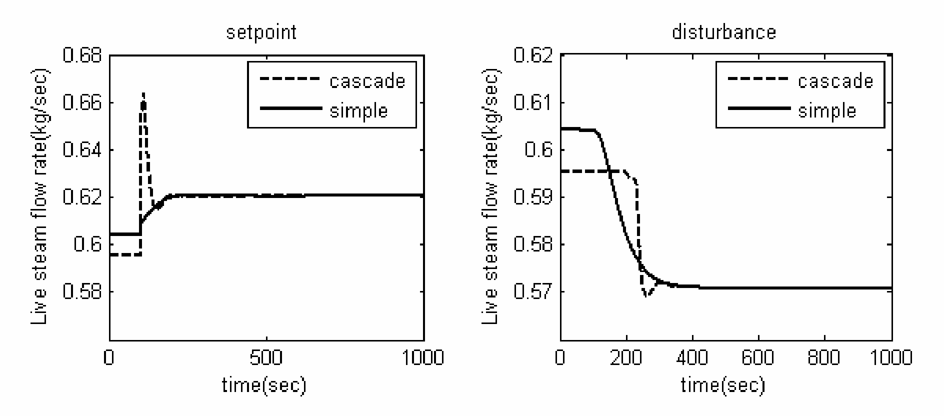

Figure 11. Performance of manipulated variable to setpoint change and disturbance.

Conclusion

In this paper, nonlinear modeling of three effect falling film evaporator is studied. By using nonlinear modeling, analysis of falling film evaporator control performance is exactly and accurately than those are used linear models. The purpose of this study was to propose a model to be inserted in a control strategy which includes as many real physical properties as possible. The final aim is to achieve a good regulation of the evaporator system with respect to normal disturbances. To this end, a knowledge model which seems to be accurate and not too complicated has been established. At first, a model of three effect falling film evaporator has been established from balance equations and semi-empirical relations.

In this study, it was specified that control of solid concentration in product solution in three effect falling film evaporator by using cascade control algorithm is possible with small delay time and a small overshoot value compare with that of simple feedback control algorithm. Present solid concentration in output solution of first and third effect can be chosen to be used in cascade control algorithm as suitable two first and second variables.

Therefore it is proposed that in the evaporation processes, correction of simple feedback algorithm and conversion it to a cascade control algorithm is more much cost-effective than the expenditure spent to buy and maintain measurement tools (sensors) and the time spent to adjust control loops.

Nomenclatur

m	mass flow rate (kg/sec)
T	temperature (^{o}C)
C	concentration (kgsolid/kgmilk)
H	enthalpy (j/kg)
Q	heat flux (j/sec)
ρ	density (kg/m^3)
V	volume (m^3)
t	time (sec)
A	heat transfer area (m^2)
U	overall heat transfer coefficient (w/m^{2}C)

Subscripts

f	feed (kg/sec)
l	concentrated milk
v	(kgsolid/kgmilk)
c	product vapor (kg/sec)
i	condensate vapor (kg/sec)
w	ith effect
PH	cool water to condenser (kg/sec)
$live$	preheater
s	live steam (kg/sec)
	first shell steam

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