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SCIENTIFIC PAPER

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CONCENTRATION OF CANE-SUGAR SYRUP IN A PILOT SCALE CLIMBING FILM EVAPORATOR

Article Highlights

- Effect of feed flow rate and steam pressure on the heat transfer coefficient is investigated
- Optimum operating parameters are determined for the concentration of sugar cane juice
- Correlation is proposed for predicting the heat transfer coefficient in a climbing film evaporator

Abstract

A climbing film evaporator is similar to a vertical tube heat exchanger, where a hot fluid, such as steam is introduced in shell side and a cold fluid such as sugar syrup is fed in tube side. In this work, variation of the overall heat transfer coefficient due to changes in process variables was investigated experimentally for concentration of cane-sugar syrup in a pilot scale climbing film evaporator. A full two-level factorial experiment was performed and significant factors were determined using Analysis of Variance. The factors investigated in this work were feed flow rate, re-circulation ratio, steam pressure, and feed temperature. The selected process response was the overall heat transfer coefficient for the climbing film evaporator. Feed flow rate and steam pressure were found to have a significant influence on the overall heat transfer coefficient.

Keywords: climbing film evaporator; statistical experimental design; heat transfer coefficient; factorial experiment.

A climbing film evaporator is a plate heat exchanger or a tubular heat exchanger consisting of tubes inside a shell, and a vapour-liquid separator at the top [1]. Steam usually flows in shell side, whereas liquid flows inside the tubes. The feed enters the bottom of the tube and starts moving upward. At the entry point, the flow is highly turbulent and film begins to form on the surface of the tube wall accelerating heat transfer rate. Climbing film evaporators are widely employed in various chemical industries to obtain a concentrated product from a dilute aqueous solution [1]. In climbing film evaporators, a high heat transfer coefficient (W/(m^2 K)) may be obtained, resulting in a relatively small heat transfer area requirement with low initial capital investment.

Climbing film evaporators are employed in various chemical industries such as fertilizer, pulp and paper, textile industries and wastewater treatment plants. Multistage evaporators have been employed in sugar industries since the first commercial implementation in 1844 in the USA [2]. In sugar industries, multiple effect climbing film evaporators are employed, where the operating temperature and pressure are higher in the first effect and lowest in the last effect [3]. Pakistan, with more than 70 sugar mills, produced 5.139 million t of cane-sugar in 2014-15 [4]. An overwhelming majority of sugar mills in Pakistan employ climbing film evaporators with shell-and-tube configuration with multiple effects for concentration of cane-sugar syrup.

Performance of climbing/falling film evaporators

Climbing/falling film evaporators have been studied previously by various researchers and perform-

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ance of such evaporators is reported in open literature in terms of rate of heat transfer. The rate of heat transfer is a function of tube size, and operating temperature difference. White [5] observed that there should be an optimum length to diameter ratio, and optimum results were obtained for a ratio of 100. Furthermore, a critical temperature difference needs to be maintained between the heating surface and the liquid that is being vaporized [5].

In a climbing film evaporator, the evaporator tube length is divided in to three main sections [6]. The first section is called the sensible heating section, where the cold fluid is heated to boiling point. The length of the sensible heating section is a function of feed temperature. The second section is the foaming section, and the length of this section lies in between the first bubble formed and the well-defined film formed on the tube wall. The length of this section is a function of feed flow rate and the physical properties of the liquid. This length is independent of feed temperature. The last section of the evaporator is the evaporating section, *i.e.*, the above foaming section. The length of this section is mainly a function of feed flow rate [6]. In climbing film evaporators, high heat transfer rate is obtained without the need for high temperature and long contact time, for obtaining concentrated product from a very weak liquor. Liquor is re-circulated to the evaporator, which increases the heat transfer coefficient and ultimately concentrates the product [7]. In climbing film evaporators, the temperature of the entering fluid is an important parameter. Feed temperature affects the surface film temperature. The height of the evaporator increases with the decrease in feed temperature, so it is useful to pre-heat the fluid entering the evaporator tube. Another advantage of pre-heating is that it reduces the risk of splashing [8].

Climbing film evaporators are also used in desalination plants, where brine solution enters tube side and hot fluid enters shell side. Uche *et al.* [9] developed a correlation for the overall heat transfer coefficient as a function of mass velocity. The overall heat transfer coefficient increased directly with increase in mass velocity. The predicted results with their proposed correlation were very similar to those obtained from experimental data [9]. Zaidi and Alam [10] observed that, with increase in heat flux, as the liquid moved up in the evaporator, the temperature of the liquid increased along the wall of the evaporator. The temperature increased very rapidly at the start, thereby increasing the heat transfer coefficient. However, once the fluid reached saturation temperature, all heat was utilized in vaporizing the liquid. At the exit, the quality of liquid was at a maximum corresponding to a decrease of the heat transfer coefficient [10].

The performance of climbing film evaporators is affected by various factors, among them the height of feed water inside the vertical tube, and the range of temperature difference between the hot and cold fluids are important factors to be taken into account. Yang *et al.* [11] showed that a high heat transfer rate is obtained for a height ratio of feed water at 0.3. Any further increase or decrease from 0.3 sharply reduces the heat transfer coefficient. Similarly, the temperature difference should be more than a critical value of 5 °C, because if the temperature difference is less than 5 °C then upward drag force is unable to bring the film to the top of the tube resulting in a decrease of the heat transfer coefficient [11].

Shah [12] investigated the influence of feed flow rate, re-circulation ratio, steam pressure, and feed temperature on the overall heat transfer coefficient in a pilot scale climbing film evaporator in which water was evaporated with steam as the heating medium. Shah [12] reported that the overall heat transfer coefficient increased from 1000 to 3000 W/(m^2 K) for an increase in Reynolds number from 800 to 1300. The overall heat transfer coefficient was found to increase with re-circulation ratio, ratio of volumetric flow rate of the recycle and feed, with a maximum corresponding to $R = 0.8$. Any further increase in the re-circulation ratio was reported to result in a decrease in U (W/(m^2 K)). The U value increased linearly from 1900 to 2300 W/(m^2 K) for an increase in feed temperature from 20 to 70 °C. The reason attributed for the increase with temperature was that less heat was consumed in a sensible heat transfer and more heat was utilized in vaporization. Increasing steam pressure was also reported to increase the overall heat transfer coefficient as with the increase in steam pressure, the temperature of steam also rises and the temperature difference between the heating surface and the feed increases, resulting in higher U values, *i.e.*, 2000 to 3000 W/(m^2 K).

Modelling and optimization of climbing/falling film evaporators

Gupta and Holland [6] studied heat transfer in a climbing film evaporator considering it as a lumped-parameter system, *i.e.*, the average values for process variables were taken into account for the experimental apparatus. The model proposed by Bourgois and Le Maguer [7] may be considered as an important milestone in modelling of climbing/falling film evaporators. However, it was based on a number of simplifying assumptions. For example, the rate of evaporation is assumed to be constant along the tube lengths.

Peacock and Starzak [13] developed a model to predict the performance of climbing film evaporators for concentration of cane-sugar syrup for various operating conditions. This model, based on the work of Zinemanas *et al.* [14] employed heat, mass, and momentum balance to predict the performance of a climbing film evaporator caused by changes in steam pressure, feed flow rate, and feed temperature. The proposed model was used to simulate efficiency of a pilot plant (Felixton mill, South Africa) for which experimental data was obtained through a factorial experiment by Walthew and Whitelaw [15].

Recent literature presents both experimental investigation of heat transfer as well as modelling of evaporators [16-19]. Fazel and Hosseyni [16] experimentally investigated the boiling heat transfer coefficient with water and ethanol as boiling liquids. Prost et al. [17] proposed a model for calculating the liquid side heat transfer coefficient as a function of Reynolds and Prandtl number. Chen *et al.* [18] measured the thickness of falling film for evaporation of pure water and seawater in a horizontal tube falling film evaporator using laser-induced fluorescence technology. Ribeiro and Andrade [19] demonstrated a simulation of climbing film plate evaporators for concentration of milk using a steady-state heat transfer model.

Various studies on optimization of climbing/falling film evaporators have also been reported [20-22]. Bhagrava *et al.* [20] developed a non-linear model for analyzing six different flow sequences of feed for concentrating weak black liquor used in the paper industry. They reported that the model may be employed for determining the optimal feed flow sequence with a maximum error of 2%. Khademi *et al.* [21] studied optimization of a multiple-effect evaporator having six effects in a desalination plant. The effect of operating parameters such as feed flow rate and condenser pressure was determined and simulations were performed with a maximum error of 5%. Sharma *et al.* [22] developed an MS Excel based multi-objective optimization program for optimizing design of a falling-film evaporator for concentration of milk. The optimization algorithm employed in their program is the elite non-dominated sorting genetic algorithm (NSGA-II).

It is worthwhile to mention here that studies reporting heat transfer in climbing film evaporators are relatively not too abundant compared to other heat transfer devices for concentration of fluids in food processing in general, and concentration of cane-sugar syrup in particular. A review of current literature leads to the conclusion that prediction of the boiling heat transfer coefficient is difficult for fluids whose viscosity increases with concentration [23]. Pacheco and Frioni [24] investigated variation of the overall heat transfer coefficient with respect to increasing concentration of cane-sugar syrup in climbing/falling film plate evaporator.

Statistical analysis of experimental data

Design of experiments (DoE) is a suitable technique to plan experiments for collecting data efficiently, and then to analyze results using statistical methods. Design of experiments (DoE) has numerous applications in the field of Engineering such as [25]:

- Improving the performance of a manufacturing process by helping in selecting proper raw materials, machines, and measurement techniques.
- Determination of significant factors for a chemical process plant. Screening experiments are performed for this purpose, in order to determine the factors that affect the response to a greater extent.
- Reducing the number of experimental runs and taking into account interactions between factors, *i.e.*, process variables, is efficiently done through factorial designs compared to conventional approach of performing experiments, *i.e.*, one-factor-at-a-time approach.

The 2^k factorial design of experiments has been employed previously by Ahmad and co-workers for optimizing operating parameters for reaction and separation systems [26,27].

In this paper a systematic approach is presented to study variation of the overall heat transfer coefficient as a function of process parameters in a climbing film evaporator. The 2^k factorial design of experiments is chosen to study the main and interaction effects of process parameters for concentration of industrial cane-sugar syrup. Results presented here may be helpful in future studies on modelling and optimization of heat transfer in climbing film evaporators.

MATERIALS AND METHOD

Materials

The cane-sugar syrup used during experiments was obtained from Khazana Sugar Mill, Peshawar, Pakistan, having physical properties as shown in Table. 1.

The cane-sugar syrup fed into the evaporator of the Khazana sugar mill typically has a concentration of about 15 to 15.5 °Bx. This syrup has pH in range of 7 to 7.5. The temperature of the syrup before entering the evaporator is usually around 65 to 70 °C.

Table 1. Physical properties of industrial cane-sugar syrup

No	Parameter	Value
1	Viscosity	0.0036 N s/m^2
2	Specific heat (C_p) at 70 °C	3890 J/kg·K
3	Density	1094.1 kg/m^3
4	pH	7.0-7.5
5	Concentration	15.0-15.5 °Bx

Experimental setup

A climbing film evaporator, model number UOP 20 X STM, was employed for the experimental work. The evaporator employed was a double effect evaporation unit but it was operated as single effect climbing film evaporator. The schematic of the equipment is shown in Figure 1.

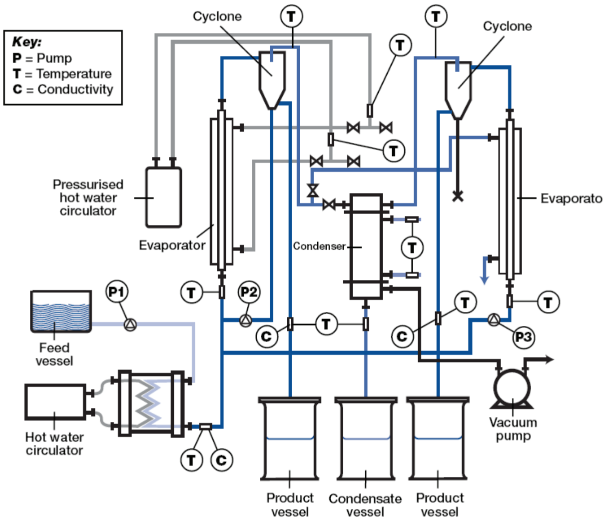

Figure 1. Schematic diagram of UOP20-PHW evaporator (www.armfield.co.uk).

It may be observed from Figure 1 that the equipment comprises of two peristaltic pumps, feed tanks, a condenser, condensate vessels, and a steam production unit.

Experimental procedure

The general procedure that was used to investigate process response consisted of the following steps:

- Steam was produced in the steam generator at the required pressure.
- Feed tank was filled with cane-sugar syrup to the desired level.
- Steam flow rate was adjusted to the desired pressure.
- Speed of feed pump, and re-circulation pump to the evaporator was adjusted.
- Cooling water flow rate in the condenser was adjusted.
- Evaporator operations were allowed to stabilize for 15 min during each experimental run before readings were noted.
- Measurements of process variables (temperature, pressure and flow rates) were noted at an interval of one minute, mean values of three readings are reported in this paper for each variable.

The factors that affect process response, i.e. the heat transfer coefficient (U, W/(m^2 K)) to a greater extent were taken into account. These are feed flow rate, re-circulation ratio, steam pressure and feed temperature. Feed flow rate selected during experiments ranged from 80 to 170 ml/min. The re-circulation ratio, defined as the ratio of volumetric flow rate of recycle to volumetric flow of feed, was varied from 0.2 to 0.8. Steam produced inside steam generator was introduced in the shell side with a pressure ranging from 0.2 to 0.5 bar. The feed was heated by means of the feed pre-heater. Feed temperature was varied from 60 °C to 80 °C.

A full two level factorial experiment was employed for this purpose. In the 2^k factorial design method there are two levels of each factor, *i.e.*, the maximum and minimum value, and the power k represents the number of factors [25]. Three centre point runs, *i.e.*, process variables at average values, were performed to augment the two-level factorial design. Centre point runs provide information about random errors, *i.e.*, variations in the overall heat transfer coefficient due to uncontrollable factors. As there are four factors, so according to the 2^k factorial design number of runs will be 16, *i.e.*, $2^4 = 16$. With additional three centre point runs, the total experimental runs performed were 19.

Calculation of the overall heat transfer coefficient

First the overall heat flow was calculated:

$$Q = mC_p(T_{\text{out}} - T_{\text{in}}) + m_v\lambda \tag{1}$$

where m = mass flow rate of feed entering tube side of the evaporator, kg/s, C_p = specific heat capacity of feed, J/((kg·K), T_{in} = Inlet temperature of feed, °C, T_{out} = Outlet temperature of feed, °C, m_v = mass flow rate of condensate, kg/s and λ = Latent heat of vaporization of feed, J/kg.

It is worthwhile to note here that cane-sugar syrup may be considered as a three-component mixture of water, sucrose, and non-sucrose dissolved solids [13]. The latent heat of vaporization of feed, *i.e.*, cane-sugar syrup can, therefore, be approximated with latent heat of vaporization of water. Latent heat of vaporization of water was taken to be 2258 kJ/kg [28].

The overall heat transfer coefficient (U) is calculated [1]:

$$Q = UA\Delta T_{\mathrm{lm}} \tag{2}$$

where A = surface area = 0.256 m^2, ΔT_{lm} = log mean temperature difference, °C and Q = overall heat transfer rate, W.

Uncertainty in calculation of the heat transfer coefficient

Calculation of the overall heat transfer coefficient for concentration of cane-sugar syrup in a single-effect climbing film evaporator was based on the state variables measured at the inlet and the outlet of the shell-and-tube configuration. The variables measured were temperature, pressure, and flow rates. Temperatures were measured using K--type thermocouples with an uncertainty of ±2.2 °C (or ±0.75% of the reading). Flow rates were measured using the variable area flow meters. The uncertainty in pressure and flow measurements is ±1% of the reading.

The value of specific heat capacity, employed in calculations, was measured at 70 °C, *i.e.*, the average temperature of cane-sugar syrup entering the evaporator tube. The use of average C_p value of feed and λ of water also contributes to the uncertainty in calculations. Therefore, the calculated overall heat transfer coefficient may be expected to have an uncertainty within ±5%.

RESULTS AND DISCUSSION

Industrial cane-sugar syrup was evaporated in a pilot scale multiple effect evaporator, employing only a single stage, for collecting data on variation of the overall heat transfer coefficient as a function of process parameters. The screening experiment was performed to determine significant factors for variation of the overall heat transfer coefficient. The results are shown in Table 2.

It may be observed from Table 2 that the overall heat transfer coefficient varies in the range of 1300 to 9300 W/(m^2 K). Higher feed flow rate and feed temperature result in higher values of U (W/(m^2 K)). The maximum value of U (9326 W/(m^2 K)) corresponds to the maximum feed flow rate and feed temperature, but the minimum re-circulation ratio and steam pressure. While the minimum value of U (1330 W/(m^2 K)) corresponds to the minimum feed flow rate and feed temperature. These results are in confirmation with previously reported trends on the increase in the overall heat transfer coefficient with increase in mass velocity, *i.e.*, feed flow rate [9,12].

Table 2. Experimental results for concentration of cane-sugar syrup in a climbing film evaporator

Feed flow rate, ml/min	Re-circulation ratio (R)	Steam pressure, bar	Feed temp. °C	U W/(m^2 K)
80	0.2	0.2	60	3510.4
170	0.2	0.2	60	7386.9
80	0.8	0.2	60	2565.7
170	0.8	0.2	60	8720.7
80	0.2	0.5	60	1330.2
170	0.2	0.5	60	4511.3
80	0.8	0.5	60	1565.5
170	0.8	0.5	60	7446.5
80	0.2	0.2	80	2239.8
170	0.2	0.2	80	9326.2
80	0.8	0.2	80	2763.2
170	0.8	0.2	80	8983.9
80	0.2	0.5	80	2132.4
170	0.2	0.5	80	6434.5
80	0.8	0.5	80	1892.7
170	0.8	0.5	80	6703.4
125	0.5	0.35	75	5588.9
125	0.5	0.35	75	4804.8
125	0.5	0.35	75	5288.5

Design Expert Trial version 9.0.6 was used to find the contribution of each factor, *i.e.*, process variables, on process response (overall heat transfer coefficient). Analysis of Variance (ANOVA) was performed to determine significant factors (operating parameters) as shown in Table 3.

Table 3. Analysis of Variance for experimental results for concentration of cane-sugar syrup in a climbing film evaporator

Source of variation	Sum of squares	*df*	Mean square	*F*	*p*-Value
Model	1.191E+008	2	5.953E+007	88.60	<0.0001
Feed flowrate	1.077E+008	1	1.077E+008	160.31	<0.0001
Steam pressure	1.136E+007	1	1.136E+007	16.90	0.0009
Curvature	3.702E+005	1	3.702E+005	0.55	0.4994
Residual	1.008E+007	15	6.719E+005		
Pure Error	3.130E+005	2	1.565E+005		
Total	1.295E+008	18			

The correlation developed using Design Expert is a regression model:

$$U = 4905.03 + 2594.60A - 842.51B \tag{3}$$

where A = coded value of feed flow rate, *i.e.*, "-1" corresponding to minimum feed flow rate of 80 ml/min and "+1" corresponding to maximum flow rate of 170 ml/min; B = coded value of steam pessure, *i.e.*, "-1" corresponding to minimum steam pressure of 0.2 bar and "+1" corresponding to a maximum steam pressure of 0.5 bar.

Design Expert typically presents regression models in terms of coded values for variables. The constant term, *i.e.*, first term in Eq. (3), is mean value of the overall heat transfer coefficient in all experimental runs. Eq. (3) can be alternatively represented in terms of the actual values of feed flow rate and steam pressure:

$$U = -336.3 + 57.6F - 5616.7P_{\mathrm{Steam}} \tag{4}$$

where F = feed flowrate (ml/min), P_{Steam} = steam pressure (bar).

It may be observed from Table 3 that the model F-value of 88.60 implies that the model, *i.e.*, empirical correlation (Eq. (3)), was significant since there is only a 0.01% chance that a "Model F-Value" this large could occur due to noise. The R^2 for this correlation is 0.909, meaning that 91% of variability in U is explained by this correlation for experimental data. The column showing p-value is an indicator of significant factors. The p-value "<0.0001" for feed flow rate and steam pressure indicate that these two factors have a significant influence on variation of the overall heat transfer coefficient.

Furthermore, the validity of the empirical model was checked by graphical analysis of residuals.

The normal probability plot, as shown in Figure 2, shows that all the residuals except one lie close to the diagonal, confirming the validity of the model.

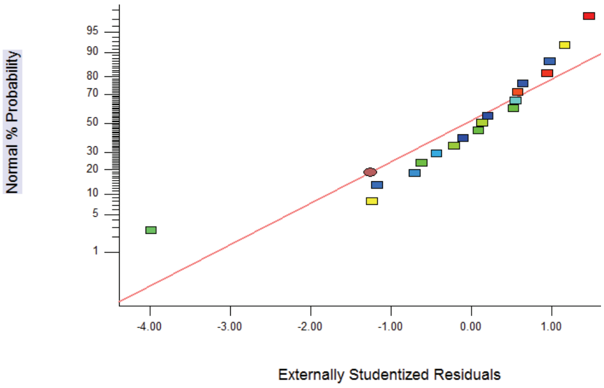

Figure 2. Normal Probability Plot for concentration of cane-sugar syrup.

It may be observed from Figure 3 that two factors: feed flow rate and steam pressure are significant based on t-values. Thus the correlation presented in Eqs. (3) and (4) is developed in terms of these two process variables. Response surface contours are shown in Figure 4 showing the overall heat transfer coefficient as a function of significant factors (feed flow rate and steam pressure).

It may be observed from Figure 4 that increasing the feed flow rate results in an increase in U as the top left corner of the response surface contour plot corresponds to ≈ 8000 W/(m^2 K) compared to the bottom right corner corresponding to ≈ 2000 W/(m^2 K). It may be worthwhile to note here that -1 and +1 correspond to the minimum and maximum values of process variables consistent with the notation generally adopted in literature on factorial design of experiments and analysis of variance [25].

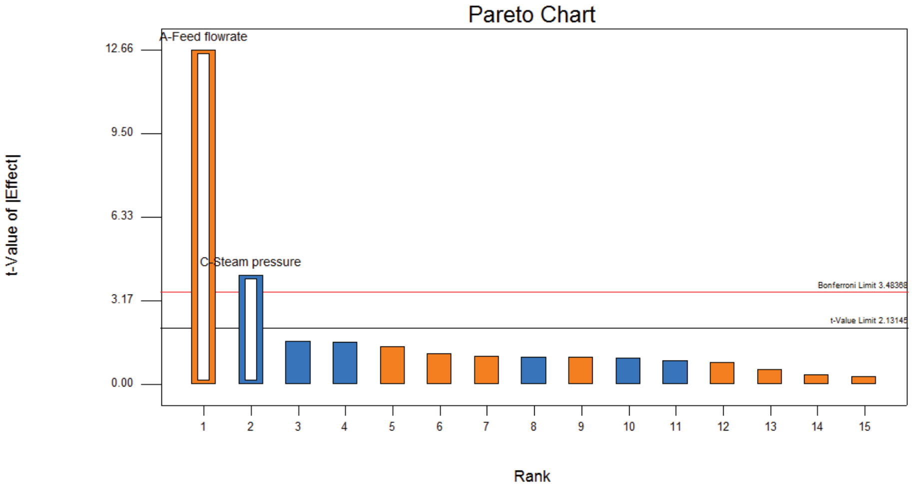

Figure 3. Pareto chart of significant factors in concentration of cane-sugar syrup.

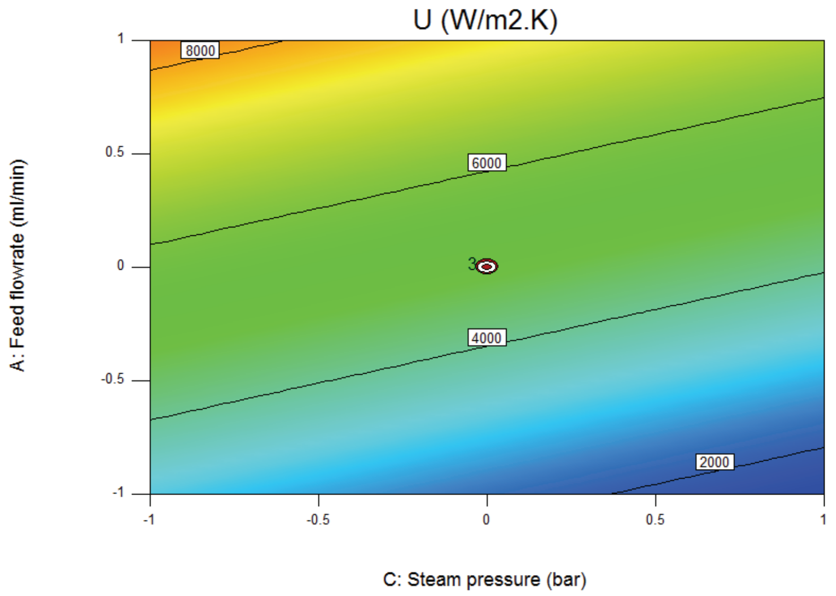

Figure 3. Pareto chart of significant factors in concentration of cane-sugar syrup.

CONCLUSIONS

The aim of this work was to determine which process variables (feed flow rate, re-circulation ratio, steam pressure and feed temperature) have a significant influence on the variation of the overall heat transfer coefficient in a pilot scale climbing film evaporator. Industrial cane-sugar syrup was concentrated with steam as the heating medium in a shell-and-tube configuration. A full two level factorial design of experiments was employed to determine the significant factors using analysis of variance. The feed flow rate and steam pressure were found to have a significant influence on the overall heat transfer coefficient in experimental runs performed for concentration of cane-sugar syrup. A correlation with an R^2 value of 0.91 is proposed to estimate the overall heat transfer coefficient as a function of feed flow rate and steam pressure. The experimental data presented may be helpful in future studies on modelling and optimization of heat transfer in climbing film evaporators.

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NAUČNI RAD

KONCENTRISANJE SIRUPA ŠEĆERNE TRSKE U POLUINDUSTRIJSKOM UZLAZNOM FILMSKOM ISPARIVAČU

Uzlazni isparivač je sličan vertikalnom izmenjivaču toplote, pri čemu se grejni fluid, para, uvodi u omotač, dok se hladna tečnost, šećerni sirup, svodi u cevi. U ovom radu eksperimentalno je istraživan ukupni koeficijent prenosa toplote u poluindustrijskom uzlaznom filmskom isparivaču pri koncentrisanju sirupa šećerne trske u različitim procesnim uslovima. Primenjen je potpun faktorijelni eksperimentalni plan na dva nivoa i utvrđeni su značajni faktori korišćenjem analize varijanse. Faktori koji su istraživani u ovom radu su bili protoka sirupa, odnos recirkulacije, pritisak pare i temperatura ulaznog sirupa, dok je odgovor bio ukupni koeficijent prenosa toplote. Utvrđeno je da protok sirupa i pritisak pare značajno utiču na ukupni koeficijent prenosa toplote.

Ključne reči: uzlazni filmski isparivač, statistički eksperimentalni dizajn; koeficijent prenosa toplote; faktorski eksperiment.