Modelling heat transfer with phase change phenomena in a spirally finned exchanger/evaporator

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In this study the overall heat transfer coefficient has been evaluated during the concentration of the industrial phosphoric acid from 28% to 54% in P_2O_5 using a spirally finned exchanger/evaporator. Experiments have been performed on a pilot unit based on a two level factorial plan. The results obtained, show that within the experimental range, the flow rate of diluted phosphoric acid has a negligible effect on the heat transfer coefficient, while the pressure of heating steam has a predominant effect. The effects of the main operating parameters have thus been incorporated into a polynomial model expressing the overall heat transfer coefficient as a function of such parameters.

1. Introduction

In the DAP factory of the Tunisian Chemical Group, the phosphoric acid with 28% P_2O_5 content is concentrated up to 54% by evaporation under vacuum. The concentration process currently used presents several problems such as the obstruction of tubes by the acid which is both very greasy and contains a significant amount of impurities; other drawbacks include losses of exergy due to significant pressure and temperature gradients present between the exchanger and the boiler (Meddeb *et al.*, 2003). In order to remedy these problems, an original process of concentration of the phosphoric acid was studied using a spirally finned exchanger/evaporator. This technique of evaporation consists in making the liquid stream (to be evaporated) flow over the surfaces of spirally configured fins around a vertical tube heated inwardly by a heating fluid (Meddeb *et al.*, 2003; Bandelier, 1997; Meddeb, 2004). The tubes and fins are manufactured from a massive single bloc of impregnated graphite (Meddeb, 2004). This exchanger/evaporator offers several advantages: a low film thickness, a hydrodynamic favourable to the heat transfer and a sufficiently long residence time insuring the desired heat exchange. Furthermore, the thermal transfer coefficients are significantly greater than those of conventional exchangers which use smooth tubes (Meddeb and Jeday, 2004; Soetrisnanto, 1992; Clauzade and Le Goff, 1988).

The objective of the present work is to study the heat transfer during phase change of a flowing solution over the surfaces of the spiral fins. The influence on the overall heat transfer coefficient of some operating parameters as well as their mutual interactions is characterised in the case of concentration of phosphoric acid. A model has thus been

constructed, giving the variation of the overall heat transfer coefficient as a function of such parameters which control the heat transfer.

2. Experimental methodology

A pilot scale unit (Meddeb, 2004) consisting of an exchanger/evaporator composed of a battery of seven spirally finned tubes in a single shell (arranged in parallel) coupled with the necessary instrumentation (control and acquisition) has been installed in the DAP factory of the Tunisian Chemical Group (coastal city of Gabes). In addition to the exchanger/evaporator, an extraction tank, a circulation pump, a vapour/acid flow separator and a vacuum creating system, were also used. The unit has been connected to a phosphoric acid concentration line of the DAP factory.

2.1 Hypotheses of calculations

The heat transfer operation occurs during phase change ; consequently, the entrance and exit temperatures of the heating steam are identical (constant condensation temperature, e.g. 110°C). The phosphoric acid solution is also considered to be at its boiling point (constant vaporization temperature of 80°C). In fact, this vaporization (phase change) has been found to start at the first fin (Meddeb 2004). According to these operating conditions, the heat flow ϕ received by the acid solution is expressed as:

$$\phi = G_c \cdot L_c \tag{1}$$

Where G_c is the heating steam flow rate and L_c is its latent heat of condensation.

The overall heat conductance, U_g, is computed with respect to the internal exchange surface, S_{int}, by the following expression:

$$U_g = \frac{\phi}{S_{int} \cdot (T_c - T_f)} \tag{2}$$

Where, T_c is the temperature of the heating steam and T_f that of the evaporating film.

2.2 Experiment matrix

In the present work, the effects of the following independent factors have been chosen to carry out the study:

• The flow rate, M_r, of recycling of industrial phosphoric acid, concentrated to approximately 54% in P_2O_5.

• The flow rate, M_a, of diluted industrial phosphoric acid whose P_2O_5 content is approximately 28%.

• The pressure, P, of the heating steam.

Table 1 Identification of the different flow regimes.

Hydrodynamic regimes	Film flowrate, M_f (l.h^{-1})		
	Water	**Phosphoric Acid at 28% in P_2O_5**	**Phosphoric Acid at 54% in P_2O_5**
Upper faces wetted *(Regime 1)*	$M_f < 60$	$M_f < 65$	$M_f < 75$
with dry zones *(Regime 2)*	$60 < M_f < 400$	$65 < M_f < 400$	$75 < M_f < 540$
All fins wetted *(Regime 3)*	$400 < M_f < 550$	$400 < M_f < 600$	$540 < M_f < 750$
Excess of overflow *(Regime 4)*	$M_f > 550$	$M_f > 600$	$M_f > 750$

Table 2 Intervals of variations of the operating parameters.

	$Mr(m^3/h)$	Mr^*	$Ma\ (m^3/h)$	Ma^*	$P\ (bar)$	P^*
Level (–)	3	-1	0,1	-1	1	-1
Level (+)	5	+1	0,2	+1	2	+1

The range of variation of the recycling flow rate, M_r, has been selected according to a previous hydrodynamic study undertaken on a prototype unit (Meddeb *et al.*, 2004). In fact, to be able to identify the different hydrodynamic regimes, M_r has been gradually varied at the inlet of the exchanger while visually observing the hydrodynamic behaviour of the falling film. Thus, four flow regimes have been identified and are gathered with related process details in table 1.

It should be noted that the range of variation of the recycling flow rate, M_r, is within the limits of the flow rates of the third regime. The pressure of the heating steam is that of the industrial line of operations. As a result, the maximal value of this pressure is an experimental constraint. The experimental range thus chosen is given in table 2, where Mr^*, Ma^*, and P^* are the reduced variables. The method of experiments planning has been used to study the effects (i.e. weights of Mr^*, Ma^*, and P^* individually) and interactions (weights of the products $M_r^*{\cdot}M_a^*$, $M_r^*{\cdot}P^*$, $M_a^*{\cdot}P^*$, and $M_r^*{\cdot}M_a^*{\cdot}P^*$) of the above reduced variables on the overall heat transfer coefficient. Experiments have been performed according to a factorial plan with two levels. The number of minimum experiments was therefore equal to 8. Modes of each considered factor corresponded to limits of the operation range (Jacgoby, 1996). In order to evaluate the experimental error, the factorial plan has been duplicated. Three replicates for the centre of the experimental matrix have been performed for validation. All experiments have been achieved in random order and the retained values are those corresponding to the established regime of the pilot scale unit.

3. Results from the pilot unit experiments

3.1 Tests matrix

Experimental results corresponding to the pilot unit are summarised in table 3.

Table 3 Tests matrix and experimental results.

Flow rate of recycling, Mr (m³/h)	Flow rate of acid, Ma (m³/h)	Pressure of heating Vapour, P (bar)	overall coefficient, Ug (W/m².°C)
5	0,2	2	3116 - 3116
4	0,2	2	2999 - 3038
5	0,1	2	2450 - 2891
4	0,1	2	3260 - 3065
5	0,2	1	2400 - 2631
4	0,2	1	2205 - 2372
5	0,1	1	2559 - 2648
4	0,1	1	2553 - 2536
4,5	0,15	1,5	2707 - 2670 - 2638

The obtained factorial plans are optimal plans and allow to determine the operating variables effects and their interactions.

3.2 Effects and interactions

Table 4 gives the effects and interactions values (E's and I's) computed by statistical formulae (Jacgoby, 1996). The experiments were duplicated in order to estimate the average typical deviation as a measurement of the error on the overall thermal exchange coefficient. An average experimental value of the typical deviation is around 142 W/m².°C which represents a relative error of about ±5%.

Table 4 Effects and interaction values: (1) effects E1, E2, E3 are Mr, Ma, and P; (2) e.g. I_{12} is the interaction of E1 and E2; (3) average value of Ug (W/m².°C)

	Effects[1]			Interactions[2]			
Average[3]	E_1	E_2	E_3	I_{12}	I_{13}	I_{23}	I_{123}
2740	-13,5	-5,2	252	94	-85	81	52

4. Modelling of the results

4.1 Mathematical model

Based on the variance of reproducibility and student test (*t*-values) (Jacgoby, 1996), the effects E_1, E_2, and the interaction I_{123} are not significant (t_1, t_2, and $t_{123} < t_{0.05}(10)$) and so have to be excluded from the equation of regression. The complete model then reduces to the following:

$$Ug = 2740 + 252\,P^* + 94\,Mr^*Ma^* - 85\,Mr^*P^* + 81\,Ma^*P^* \tag{3}$$

5. Interpretation

It appears from the model effects and interactions (Eq. 3), that the most important effect is that of the pressure (*P*). This shows that the heating steam side resistance predominates during heat transfer process. An increase of the heating vapor pressure improves the overall heat transfer coefficient. In fact, any increase of the pressure will lead to an increase of the heat transfer coefficient. But, if the pressure of the condensing vapor (saturated vapor) increases, its temperature also increases. This increase of the difference between the temperature of the wall and that of the boiling solution leads to the formation of bubbles (Carey, 1992), thus explaining the positive effect of the pressure of condensing vapor. The recycling flow rate of the phosphoric acid (M_r) which practically represents the film flow rate ($M_f = M_r + M_a \approx M_r$) in the evaporator does not have a significant effect on the overall heat transfer coefficient (U_g). This may be due to the choice of the range of variation of this parameter. Indeed a study on a prototype unit (Meddeb, 2004) showed that the U_g is constant in the course of the third flow regime. This appears on Figure 1 which shows a leveling off of U_g over a significant portion of the range of variation of the acid solution film flow rate (M_f). The level of heat transfer coefficient is influenced by the heating vapor flow rate. The overall heat transfer coefficient varied between 1.5 to 2.5 kW/m².K ; this compares well with the results cited by other works (Bandelier, 1997). Values of U_g corresponding to the pilot unit (tube length of 1.5 m) ranged from 2.2 to 3.1 kW/m².K (Table 3).
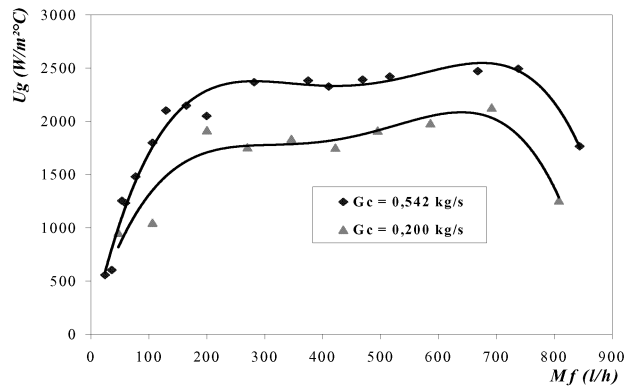
Fig. 1. Variation of the overall heat transfer coefficient as a function of the flow rate of 54% P_2O_5 phosphoric acid, for two heating steam flow rates.

Figure 2 gives the variation of the relative error according to the value of the overall heat transfer coefficient (U_g).
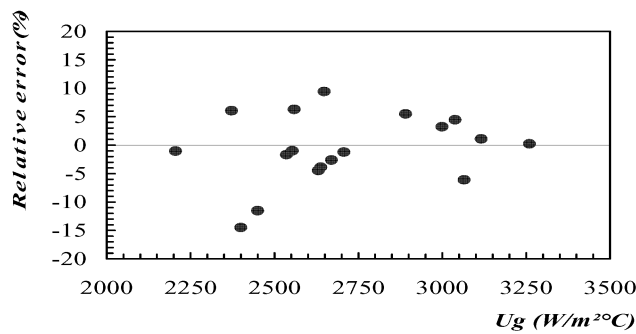

Fig. 2. Variation of residues with respect to the overall heat transfer coefficient, Ug.

Likewise, the flow rate of the dilute phosphoric acid solution (M_a) does not have a notable effect. Since this flow rate is much lower than the recycling one (M_r), its influence on the thermal transfer process will be further insignificant. Although the effects of the flow rates of the dilute and recycling phosphoric acid are not important individually, their interaction is significant. If the flow rates of the dilute and recycling phosphoric acid are increased while increasing the ratio (M_r/M_a), the heat transfer is enhanced; this observation explains the positive value of the interaction (I_{12}).

Due to the predominant effect of the heating steam pressure, interactions of the first order involving this factor and any other factor will be significant. It is the case of the interactions (I_{13}) and (I_{23}) despite the fact that they are at the limit of the acceptable significance (*t*-values are close to the tabulated standard one). The negative interaction (I_{13}) may be explained by the fact that when the recycling flow rate increases, the temperature also increases, leading to a decrease in the temperature gradient. This decrease attenuates the nucleate boiling phenomena leading to a fall of the overall thermal exchange coefficient. In contrast, the positive interaction (I_{23}) is explained by

the fact that any increase of the dilute acid flow rate (having a lower temperature) leads to a reduction of the temperature of the solution, and any increase of the condensing vapour pressure favours an increase of its temperature. Consequently, the temperature difference grows in these conditions leading to a better overall thermal exchange coefficient. The average density of the exchanged thermal flow is in the order of 110 kW/m^2. According to the bibliographical study (Carey, 1992) the surface evaporation is dominant for densities of heat flow of about 100 kW/m^2. The nucleate boiling appears when the temperature difference between the surface and the liquid film is between 10 and 50°C. In this study, the maximal temperature difference is between 30 and 40°C.

6. Conclusion

A pilot scale unit consisting of a spirally finned exchanger/evaporator has been installed to concentrate the diluted phosphoric acid. The variation of the overall heat transfer coefficient (U_g) as a function of the different operating parameters controlling the heat transfer process such the recycling acid solution flow rate (M_r), the diluted acid solution flow rate (M_a), and the heating vapor pressure (P), has been modeled based on the planning of experiments method. The analysis of residues and application of statistical tests have shown that this model adequately describes the experimental results. Within the considered experimental range, the relative error on (U_g) given by the model is less than 15%. The vapor side heat resistance controls the overall transfer process. And so the overall heat transfer coefficient was predominantly affected by the pressure of the heating vapor.

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