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A Continuous Model of a Rotating Disc Column for Glycerol Recovery in Soap Production

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Since several decades Rotating Disc Columns (RDC) are adopted in soap production plants for the recovery of glycerol from the liquid soap effluent of the saponification reactor. Of course axial dispersion widely affects the efficiency. A theoretical approach to the problem is here presented. Model predictionS concerning glycerol, NaOH, NaCl concentrations have been compared with experimental data obtained from a commercial column and the comparisons appear to be very satisfactory.

1. Introduction

The soap production plant considered is continuous. It is essentially constituted by four sections: saponification, washing, separation and neutralization section. Here the attention is focused to the washing section where the glycerol, which is an important by-product, is separated from soap phase. This operation is often performed in a RDC column as illustrated in figure 1. Stator rings are positioned over the column internal surface in order to reduce axial mixing. Soap solution mainly containing soap, water and glycerol is contacted with a lye constituted by water, NaOH and sodium chloride. Usually lye, being heavier and less viscous, is preferred as dispersed phase for reducing axial dispersion and then optimizing the global mass transfer. The typical operating temperature is about 85-90°C and the pressure is atmospheric. The shaft rotates at about 80-90 rpm. Total soap flow-rate is close to 3000 kg/h. Both mixing and mutual dispersion of the phases is due to rotor movement, that increase the mass transfer but that also results in important detrimental axial dispersion. The term "axial" essentially refers to the macroscopic direction of contact between the two phases. It causes a very drastic reduction in the overall efficiency of the apparatus, such to make equipment size considerably larger than the ideal one. Just as an example in the present

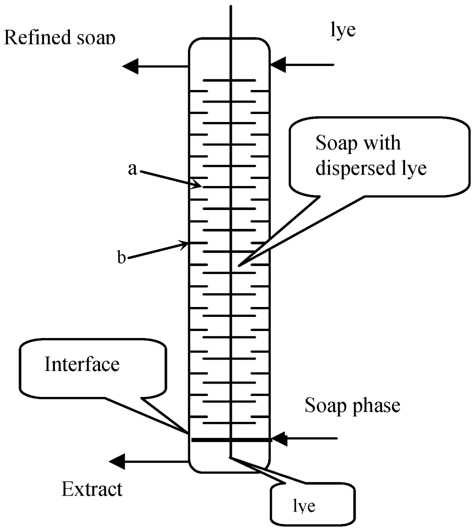


Figure 1 - Rotating disk contactor (RDC). a) Rotating disk; b) Stator ring

case the number of real contacting sections compared to the theoretical stages, is roughly ten time more.

An adequate prediction of axial dispersion coefficients is therefore essential to the aim of modeling the column behavior. Relevant studies of RDCs have been carried out by Korchinsky and Azimzadeh-Khatayloo (1976), Chartres and Korchinsky (1975), Cruz-Pinto and Korchinsky (1980) and many others researchers. Those models are frequently based on empirical equations (mainly based on experimental data related to lab scale columns), and on stage-wise approaches. More recently droplet population balance modeling (Attarakih et al. 2006a, 2006b, Schmidt et al., 2006) has been adopted. Here a different approach is proposed. It is based on the average size of the drops even if different researchers (Rod (1966), Misek and Rod (1971), Misek and Marek (1970), Pratt and Stevens (1992)), have stated the importance of discrete character of the drops distribution (different residence times, velocities and different modes of mass transfer). An original method of evaluating axial dispersion coefficients is also proposed. The method is similar to one already successfully tested by the authors for an other kind of liquid-liquid extractor (M. Dente and G. Bozzano, 2004). Moreover is has to be pointed out that this work represents something new in the field of RDC modeling in soap production.

2. Drop size, velocity and hold-up of the dispersed phase (lye)

Drop sizes are related to the action of turbulent eddies produced by rotor movement. Referring to Kolmogorov theory, with some adaptations, it has been deduced the following expression for the average drop diameter:

$$D_d \cong 0.65\left(\frac{\sigma}{\rho}\right)^{3/5} \varepsilon_T^{-2/5} \qquad 1)$$

ε_T is the power dissipated per unit mass: it is obtained from the power of each disk divided by the mass contained into the stage ($\rho_{mix}\, V_{stage}$):

$$\varepsilon_T = 15.2\frac{D_R^4 \nu_{mix}^{0.5} N^{2.5}}{D_C^2 H_S} \qquad \text{where } \nu_{mix} = \nu_c/(1-\phi)^2 \qquad 2)$$

The asymptotic velocity of the drops can be estimated by means of the following expression (deduced by the balance of forces coupled with the proper friction factor):

$$v_0 \cong \left(\sqrt{1+x}-1\right)\frac{12\mu_S k}{\rho_S D_d} \qquad \text{with} \quad k = \frac{1+2\mu_S/\mu_L}{1+3\mu_S/\mu_L} \quad \text{and} \quad x = \frac{1}{108}\frac{\rho_S \Delta\rho g D_d^3}{\mu_s^2 \cdot k^2} \qquad 3)$$

$$f = \frac{2 \cdot F_{res.}}{\rho_S \cdot v_0^2 \cdot \frac{\pi \cdot D_d^2}{4}} \cong 1 + \frac{24 \cdot \mu_S}{\rho_S \cdot v_0 \cdot D_d} \cdot \frac{1+2\cdot\mu_S/\mu_L}{1+3\cdot\mu_S/\mu_L}$$

The absolute falling velocity of the single drop is reduced by the hold-up, but it is also related to the superficial velocity of the two phases. Therefore the hold-up can be deduced from expression 4) obtained by combining the two contributions:

$$v_0(1-\phi)^2 = \frac{v_S}{1-\phi} + \frac{v_L}{\phi}$$

Figure 2 shows a comparison of the hold-up obtained from the proposed theory and experimental data deduced from M.A. Moris *et al.* (1997). The comparison is satisfactory.

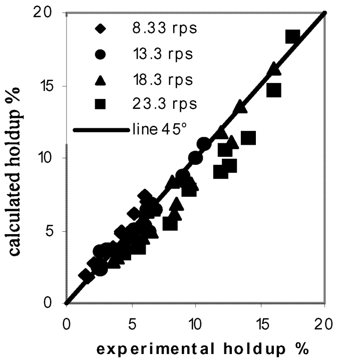


Figure 2: Calculated versus experimental holdup

3. Mass transfer and axial dispersion coefficients

The mass transfer coefficients for soap and lye phases are evaluated as follows:

$$K_{S,i} = 2\frac{\mathcal{D}_{\text{diff},S-i}}{D_p} + 1.12\sqrt{\frac{\mathcal{D}_{\text{diff},S-i}}{t_{\text{cont.}}}} \qquad K_{L,i} = \frac{2}{3}\pi^2\frac{\mathcal{D}_{\text{diff},L-i}}{D_p} + 1.12\sqrt{\frac{\mathcal{D}_{\text{diff},L-i}}{t_{\text{cont.}}}} \qquad 5)$$

The proposed expressions are the result of combining asymptotic behaviors. The contact time is related to the velocities of turbulent fluctuation at the drop size scale: $v_{\text{cont.}} \cong (\dot{\varepsilon}_T D_d)^{1/3}$. The velocity of the interface can be estimated in order of magnitude as half of the one of turbulent eddies, so that the drop interface contact time can be expressed as: $t_{\text{cont.}} = 1.5\left(\frac{\sigma}{\rho_{\text{mix}}}\right)^{2/5} \dot{\varepsilon}_T^{-3/5}$

Axial dispersion depends on the flowrate circulating around the disk (above and below):

$$Q = 1.8 \cdot \frac{\pi D_r^2}{4} \cdot (\nu_c \cdot \omega)^{1/2} \qquad 6)$$

Due to the symmetry of the system, the relevant velocity is therefore,:

$$v_{car} = \frac{2Q}{\pi D_C^2} = 0.9\left(\frac{D_R}{D_C}\right)^2 (\nu_c \cdot \omega)^{1/2} \qquad 7)$$

Each recirculation covers approximately ¼ of the stage height (then the axial mixing length is $\lambda = H_s/4$). Axial dispersion has been therefore estimated as one half the product of this characteristic length and velocity:

$$\mathcal{D}_{ax} = \frac{v_{car}\lambda}{2} = 0.28\left(\frac{D_r}{D_c}\right)^2 (\nu_c N)^{1/2} \cdot H_s \qquad 8)$$

4. The evolution of composition along the column

The column is essentially isothermal so that its behaviour can be represented only by means of mass balances. The high number of real stages with respect to the theoretical ones suggests to adopt a "continuous" model, instead of a "Stage-wise". The mass balance for the generic species "i"in both the phases it given by:

$$
\begin{aligned}
&v_L\rho_L\frac{d\omega_{i,L}}{dz} = \mathcal{D}_{ax,L}\rho_L\frac{d^2\omega_{i,L}}{dz^2} + k_{tot,i}\left(\frac{\rho_s\omega_{i,s}}{keq_i} - \rho_L\omega_{i,L}\right)\\
&-v_S\rho_s\frac{d\omega_{i,s}}{dz} = \mathcal{D}_{ax,s}\rho_s\frac{d^2\omega_{i,s}}{dz^2} - k_{tot,i}\left(\frac{\rho_s\omega_{i,s}}{keq_i} - \rho_L\omega_{i,L}\right)
\end{aligned}
\qquad 9)
$$

The boundary conditions are the usual ones typical of significant presence of axial dispersion:

$$
z = L_C \quad \frac{d\omega_{i,L}}{dz} = 0 \qquad\qquad z = 0 \quad \left(v_L\omega_{i,L} - \mathcal{D}_{ax,L}\frac{d\omega_{i,L}}{dz}\right)_{z=0} = v_L\omega^0_{i,L}
$$

$$
z = L_C \quad \left(v_S\omega_{i,s} + \mathcal{D}_{ax,S}\frac{d\omega_{i,s}}{dz}\right)_{z=L_c} = v_S\omega^{L_C}_{i,s} \qquad z = 0 \quad \frac{d\omega_{i,s}}{dz} = 0
$$

It has been assumed that the repartition coefficients at the equilibrium, the mass transfer coefficients and the phase densities are so weakly variable with the composition along the column that only averages of their values can be used. Then the system of equations can be considered as an homogeneous, linear system with constant coefficients.This simplification is demonstrated acceptable from the comparison with experimental data. The integration of the system produces the following expressions:

$$
\omega_{i,L} = \frac{A_0}{\rho_L} - \sum_i \frac{A_i}{\rho_L}\exp(\lambda_i\xi) \qquad\qquad \omega_{i,S} = k_{eq}\left[\frac{A_0}{\rho_L} - \sum_i \frac{m_i A_i}{\rho_L}\exp(\lambda_i\xi)\right]
$$

where: $\xi = \frac{z}{L_C}$ $\qquad m_i = 1 + \frac{v_L}{k_{tot}L_C}\lambda_i - \frac{\mathcal{D}_{ax,L}}{k_{tot}L_C^2}\lambda_i^2 \qquad (i = 1,2,3)$

A_0, A_1, A_2, A_3, are the integration constants, while λ_i are the solutions of the characteristic equation:

$$
\lambda^3 + (Pè_S - Pè_L)\lambda^2 - \left[Pè_S Pè_L + \frac{k_{tot,i}L_C}{v_L}\left(Pè_L + \frac{v_L}{keq_i v_S}Pè_S\right)\right]\lambda - \frac{k_{tot,i}L_C}{v_L}Pè_S Pè_L\left(1 - \frac{v_L}{keq_i v_S}\right) = 0
$$

where Pè is the Pèclet number defined as: $\frac{v_i L_C}{\mathcal{D}_{ax}}$ ("i" indicate the soap or lye phase). In order to overcome eventual numerical problems (due to the high absolute value of the exponentials arguments) the constants have been simplified as in the following:

$$
A_0 \cong \rho_S\omega^0_{i,s} + \frac{B}{C}\left[\frac{\lambda_1}{\lambda_2}\frac{m_3}{m_2}\left(\frac{\lambda_2}{Pè_L} - 1\right) - \frac{\lambda_1}{\lambda_3}\left(\frac{\lambda_3}{Pè_L} - 1\right)\right] \qquad\qquad A_1 \cong -\frac{B}{C}\exp[-(\lambda_1 - \lambda_3)]
$$

$$
A_2 \cong -\frac{\lambda_1}{\lambda_2}\frac{m_3}{m_2}\frac{B}{C} \qquad\qquad A_3 \cong \frac{\lambda_1}{\lambda_3}\frac{B}{C}
$$

where B e C correspond to:

$$
B = \rho_L\omega^0_{L,i} - \frac{\rho_S\omega^{L_c}_{S,i}}{k_{eq}} \qquad C = \lambda_1\left[\left(\frac{m_3}{\lambda_3} + \frac{m_3}{Pè_S} - \frac{m_1}{\lambda_1} - \frac{m_1}{Pè_S}\right)\exp(\lambda_3) + \frac{1}{Pè_L} + \frac{m_3}{m_2}\left(\frac{1}{\lambda_2} - \frac{1}{Pè_L}\right) - \frac{1}{\lambda_3}\right]
$$

5. Results and comparisons

The model has been validated by comparing the simulation results with experimental data obtained in a commercial plant. The figures show some comparisons. Samples have been analysed by using standard methods. Column geometry is: D_C=1.1 m, H_s = 0.16 m, L_C = 6.84 m, D_R= 0.72 m. In Table 1 other comparisons are reported, regarding the global efficiency of the column.

Table 1

	Soap outlet exp.	Soap Outlet calc.	Lye outlet exp.	Lye outlet calc.
	% w/w	% w/w	% w/w	% w/w
Glycerol	0.25	0.28	37.3	38.2
	0.40	0.25	33.8	34.5
	0.54	0.72	40.1	41.0
	0.30	0.39	40.8	41.9
	0.20	0.15	36.2	37.1
	0.25	0.31	35.4	36.2
NaCl	0.80	0.95	6.2	6.2
	0.80	0.86	5.8	5.5
	0.70	0.80	6.4	5.4
	0.75	0.92	6.0	6.4
	1.15	1.15	9.0	9.0
	1.20	1.00	9.2	8.9
	1.20	1.22	8.7	9.1
NaOH	0.50	0.65	1.4	1.3
	0.45	0.62	1.3	1.1
	0.55	0.65	1.4	1.2
	0.65	0.67	1.5	1.2
	0.95	0.98	1.4	1.6
	0.90	1.20	1.2	1.7
	0.90	0.96	1.2	1.7

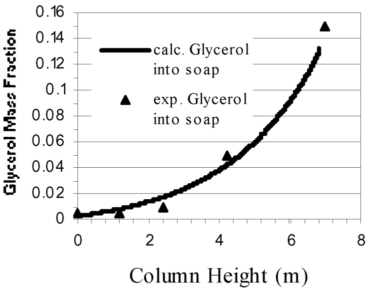
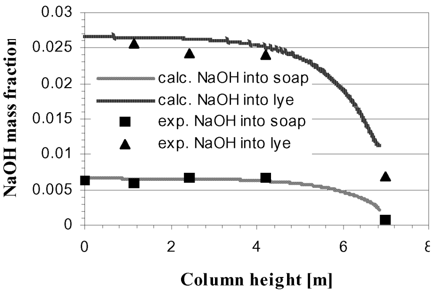


Fig. 3: Glycerol versus column height



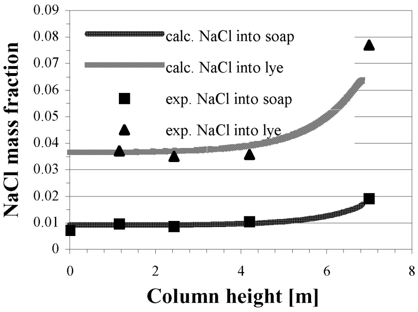


Fig.4 NaOH versus column height

Fig.5: NaCl versus column height

6. Conclusions

The comparison among model prediction and experimental data, concerning glycerol, NaOH, NaCl are very satisfactory. Also the comparison with experimental hold-up is good. So it can be concluded that the proposed simplified model represent conveniently the behavior of the equipment.

7. Acknowledgments

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8. Nomenclature

$\mathcal{D}_{ax}$ = axial dispersion coefficient
$\mathcal{D}_{diff,i}$ = diffusion coefficient of component “i” in the phase
D_C = column diameter (m)
D_d = drop diameter (m)
D_R = rotor diameter (m)
$k_{tot,i}$ = global mass exchange coefficient of component ‘i’ between lye and soap bulk referred to the column volume = $k\ (6/D_d)\ \phi$
keq,i =mass repartition coefficient of component ‘i’ into soap phase and into lye at the equilibrium
H_S = stage height (m)
i = index for component glycerol or NaOH or NaCl
L = lye phase index
L_C = length of the extraction section of the column
N = revolutions per second of the rotor
S = soap phase index
v = average phase velocity (m/s)
Q = recirculated flowrate (m^3/s)
z = cohordinate along column axis mesured from the upper part (where lye enters)
ε_T = power per unit mass of the single stage
ϕ = dispersed phase hold-up
μ = viscosity
ν_c = kinematic viscosity of the continuous phase (m^2/s)
ρ = phase density
ρ_{mix} = density of the mixture of two phases
$\Delta\rho$ = difference of density between the two phases
σ = interfacial tension (N/m)
ω = disk velocity (radiant/s) = $2\ \pi\ N$
$\omega_i^{L_C}$ = mass fraction of component “i” at $z = L_C$ (soap inlet)
ω_i^0 = mass fraction of component “i” at $z = 0$ (lye inlet)

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