(Novak, 1976). It should be emphasized that mass transfer at a given very low Reynolds number could result in much different Sherwood numbers depending on whether the fluid was a gas or liquid. This would likely be the result of the different values of the respective Peclet numbers.

In order to investigate the relationship between $\delta\xi$, Pe, and St_L for the LPDF model, Equations (1) to (3) were solved numerically by using the Crank-Nicholson implicit method. Numerical convergence was based on the liquid phase concentration and an overall material balance criterion.

Results of the numerical computations are illustrated in Figures 1 and 2. Figure 1 is a shock layer profile for the problem defined in Table 1. The shock layer thickness ($\delta\xi$) can be determined from this profile by the procedure defined by Rhee and Amundson (1972). Figure 2 was developed by using the information in Table 1 and varying the effective diffusivity (D) and overall mass transfer coefficient (K_L). The values chosen for D and K_L are thought to be within a reasonable range expected for soils based on the work by Shah et al. (1975) and Kirda et al. (1973). Curve A in Figure 2 can be seen to be consistent with Equation (9) over the range studied. However, curve B has a slope of -0.84 in contrast to a slope of -1.0 as predicted by Equation (9) for the SPDF model. Based on the information presented here, it appears that the LPDF model may not result in the same Peclet and Stanton number dependency as the SPDF model for strongly nonlinear problems (A relatively large). However, it should be recalled that the Stanton numbers for the LPDF and SPDF models are different, and a simple linear relationship between the Stanton numbers only exists for linear isotherms. Under these conditions, a shock layer does not exist.

The overall mass transfer coefficient (K_L) could be determined by the following procedure. First, the adsorbent-adsorbate system would need to be characterized by measurements of K, b, M_o, a, ϵ, ρ_p, and ρ_L. For a given V_p, one would need to determine D. This would likely be done indirectly by determining the tortuosity factor for the bed by use of an inert tracer. Then, for a given adsorbate inlet concentration, one could experimentally determine the shock layer thickness ($\delta\xi$). This information would be used to generate curve B (Figure 2) for the particular adsorption problem, and K_L could then be calculated from the St_L corresponding to the experimental $\delta\xi$.

NOTATION

A = Langmuir equilibrium characteristic = KC_o
a = fluid-solid interfacial area per volume of porous media (or packed bed)
b = Langmuir adsorption maximum
C = fluid phase concentration
C_1, C_2 = constants
D = effective diffusivity
$\mathfrak{D}$ = ordinary diffusion coefficient
K = Langmuir equilibrium constant
K_L, K_s = overall interphase mass transfer coefficients
L = characteristic length
M = solid phase concentration
N = Langmuir adsorption characteristic = $K(b - M_o)$
Pe = Peclet number = V_pL/D
Pe' = Peclet number = $V_pL/\mathfrak{D}$
St_L = Stanton number = K_LaL/V_p
St_s = Stanton number = K_saL/V_p
t = time
V_p = pore velocity
X = dimensionless solid phase concentration = M/M_o
Y = dimensionless fluid phase concentration = C/C_o
z = distance from bed inlet

Greek Letters

ρ = density
ϵ = porosity
τ = dimensionless time = tV_p/L
ξ = dimensionless distance = z/L
$\delta\xi^*$ = dimensionless saturation front thickness
$\delta\xi$ = dimensionless shock layer thickness

Subscripts

o = inlet condition
p = particle
L = liquid phase
s = solid phase

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A Modified Crystallizer Design for Specialized Applications

DALJIT SINGH

Punjab Agricultural University
Ludhiana, India

The utility requirements of evaporative vacuum crystallizers may be reduced substantially (sometimes by as much as 90%) by a simple design modification discussed in this paper.

A schematic diagram of the conventional evaporative crystallizers is shown in Figure 1 *a*. A warm, saturated solution is fed to a lagged closed vessel that is maintained under vacuum. The solution cools adiabatically to the boil-

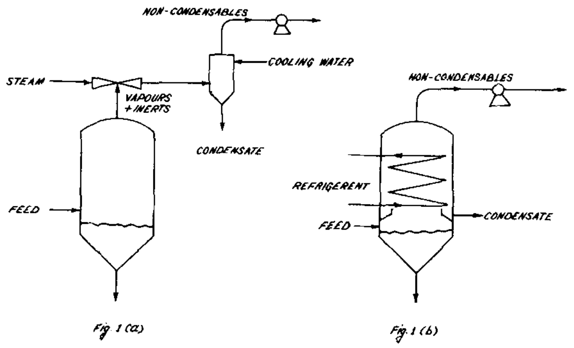

Fig. 1.(a) Conventional evaporative crystallizers, (b) modified crystallizer design.

TABLE 1. UTILITIES REQUIREMENTS FOR THE GLAUBERS SALT CRYSTALLIZERS

	Conventional	Modified design
Steam, kg/hr	11 000	—
Cooling water, m³/hr	91	22.5
Refrigeration, ton	—	40
Electricity (including that required for refrigeration unit) kwh/hr	40	70

TABLE 2. OPERATING DATA FOR CRYSTALLIZATION OF GLAUBERS SALT FROM RAYON SPIN BATH SOLUTIONS

1. Crystallization capacity	1 040 kg/hr (25 TPD) glaubers salt
2. Amount of solution to be processed	1 790 kg/hr (43 TPD)
3. Feed solution characteristics	
3.1 Solution coming from	Reactor
3.2. Composition of solution	25% Na_2SO_4 72% H_2O 3% Impurities
3.3. Temperature of solution	323.15°K
3.4. Density of solution	1 100 kg/m³
3.5 Heat of crystallization	62 kcal/kg of glaubers salt crystallized
4. Final solution from evaporation	
4.1. Composition required	750 kg/hr (18TPD) of 8% solution
4.2. Temperature of solution	283.15°K
4.3. Solution going to	Filtration unit

ing point of the solution corresponding to the vacuum in the vessel. A part of the solution also gets vaporized. Crystallization occurs as a result of cooling and vaporization. The vapors produced are carried away by means of a vacuum pump or a steam jet ejector. Steam jet ejectors can attain a very low vacuum, have very few moving parts, and are used more often. Such units, however, have very high steam requirements. The cooling water requirements are also very high. For example, the steam requirement for a 1 040 kg/hr-(25 TPD) glaubers salt unit operating in Western India was approximately 1 000 kg/hr. The exact utility consumptions are given in Table 1. The characteristics of the solution and other operating data are given in Table 2. These utility requirements account for a major portion of the processing cost and may be reduced substantially by the design modification outlined below.

MODIFIED DESIGN

A schematic diagram of the modified design is given in Figure 1 *b*. A refrigerated condensing coil is installed within the flash chamber, where a large fraction of the vapors gets condensed. The condensate is collected below the condensing coils and removed from the system. The remaining vapors and noncondensibles are evacuated as usual. However, the steam requirement for the ejector is reduced substantially owing to the reduced vapor load. In most cases, the ejector can be eliminated completely and a vacuum pump used directly, thereby eliminating the use of steam. Such a system is shown in Figure 1 *b*. Where a boiler has to be installed only for the crystallization unit, this represents a considerable saving in capital investment also.

The utility requirements for the same glaubers salt crystallization have been worked out for this design also and compared with those of the conventional designs in Table 1. The savings in utility requirements are obvious.

APPLICATIONS

Obviously, such designs will be economical only where the vapor pressure of the solution in the flash chamber is very very low, and barometric condensers cannot be employed directly. This would frequently occur where a single salt is to be recovered from an aqueous solution of mixed electrolytes. Crystallization of glaubers salt and anhydrous sodium sulfate from rayon spin bath solutions can be highly economical with such a unit. Since refrigeration is already available in such plants, there are no additional fixed costs. These crystallizers can also find application in recovery of borax from mixed brines and in recovery of certain salts from seawater and its concentrates. In fact, the increased emphasis on recovery of minerals from seawater may give a strong impetus to further development of such crystallizers. The exact economics, of course, will vary from region to region and can be evaluated for any particular application. In general, however, these crystallizers are likely to be economical for the aforementioned applications.

LIMITATIONS

The operation of such a crystallizer is based on very low driving forces and hence requires careful calculations and a delicate optimization. The lower temperature limit for the condenser coils is set by the freezing point of water inside the flash chamber. The upper temperature limit is determined by the vacuum to be maintained in the crystallizing chamber and the temperature of the crystallizing solution. This normally leaves a very low temperature differential requiring large heat transfer areas. For optimal performance, the condensing coils have to designed to provide a high heat transfer area and maximum contact without excessive pressure drop on either side.

These crystallizers are likely to find their greatest application in partial crystallizations from aqueous multicomponent electrolyte solutions. The lack of suitable thermodynamic data for such systems poses a major design limitation. For seawater solutions, the thermodynamic data and correlations of Bromley et al. (1974) provide a reasonable design base. For other electrolyte solutions, Bromley's individual ion coefficients (1973) may be used along with his extended Debye Huckel correlations.

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