R & D NOTES

Amplification of the Scale-Up Procedure for the Reciprocating Plate Extraction Column

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The main purpose of this paper is to show that the previously published procedure for scaling up a reciprocating plate extraction column leads to a simple new relationship for scaling up the energy input.

Designing an extraction column from basic principles without test work is very risky. Some of the main reasons are:

1. The degree of coalescence and interfacial turbulence effects of droplets in commercial systems cannot be predicted accurately. It is well known that mass transfer from the dispersed to the continuous phase can markedly increase the coalescence rate, as shown by Groothuis and Zweiderweg (1960). A rapid coalescence rate increases drop size, which, in turn, necessitates high energy inputs to produce satisfactory area for mass transfer. On the other hand, if droplets have little tendency to coalesce, the energy inputs have to be minimized to control entrainment, and mass transfer rates may be low.
2. Physical properties and flow rates may vary throughout the length of the column, and, as shown by Jiricny and Prochazka (1980), the holdup and drop size will vary throughout the length of the column unless some means are taken to overcome these variations. For example, for the reciprocating plate extraction column, Karr (1980) showed that the plate spacing in the column can be calculated as a function of physical properties and flow rate in order to make the tendency to flood the same everywhere in the column. However, the calculation procedure does not take coalescence into account.
3. Most commercial systems are contaminated, frequently by surface active components. Skelland and Caenepeel (1972) have shown that the degree and type of contamination can have a marked effect on mass transfer rates.
4. Axial mixing data for the dispersed and continuous phases in large diameter columns are not usually available.

Therefore, in general, it is necessary to do test work in a pilot-scale column in order to categorize the system. Once the system is categorized and the test column has been optimized with respect to volumetric efficiency and plate spacing in a reciprocating plate extraction column, the scale-up procedure given by Karr (1980) can proceed.

Data on the mass transfer performance characteristics of the reciprocating plate extraction column have been reported by Karr (1959, 1980), Karr and Lo (1971, 1976), Lo and Karr (1972), and Sharma and Baird (1978). These papers show that in small diameter columns, 50 to 150 mm, the lowest value of HETS occurs close to the flood point for low interfacial tension systems. For high interfacial tension systems there may be shallow minima in the HETS vs. f curves. As the diameter of the column is increased, the minimum in the HETS vs. f curve gets steeper because of increased axial mixing. Performance is improved by employing baffle plates periodically in the plate stack because the axial mixing is reduced, as shown by Karr and and Lo (1971, 1976), but the minimum in the HETS, vs. f curve persists. The objective of the scale-up procedure is to predict the location of the minimum in the HETS vs. f curve. For convenience the scale-up procedure is reviewed below.

SCALE-UP PROCEDURE

The scale-up procedure for the reciprocating plate extraction column is based on performance data obtained in 25, 76, 305 and 914 mm dia. columns by Lo and Karr (1972), Karr (1959), and Karr and Lo (1971, 1976), respectively.

Data are obtained in a 25, 50, or 75 mm dia. column. The diameter selected is frequently determined by the availability of feed materials. Many successful scale-ups have been done directly from the 25 mm column. The 50 and 75 mm pilot-plant columns may be used for scale-up development where the production column is in excess of 700 mm in diameter.

The optimum performance of the pilot column is determined. The criterion for optimum performance is maximum volumetric efficiency in a column having optimum plate spacing, as reported by Karr (1980).

When scaling up from the pilot data the following parameters are held constant: plate spacing, stroke length, and throughput per unit cross-sectional area.

The expected minimum HETS in the large diameter column is calculated from the following equation:

$$\frac{(\mathrm{HETS})_2}{(\mathrm{HETS})_1} = \left(\frac{D_2}{D_1}\right)^{0.38} = \frac{H_2}{H_1} \tag{1}$$

The 0.38 exponent was determined for a high interfacial tension system. Somewhat lower exponents were determined for a low interfacial tension test system and lower exponents were also confirmed by various case histories. The 0.38 exponent is used for reasons of conservatism. This is discussed further below.

The reciprocating speed required for minimum HETS is calculated from Eq. 2:

$$\left(\frac{f_2}{f_1}\right) = \left(\frac{D_1}{D_2}\right)^{0.14} \tag{2}$$

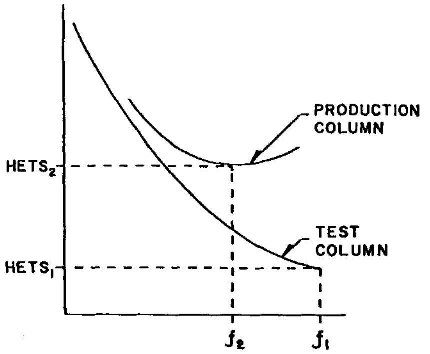

Figure 1. Effect of column size on optimum HETS and optimum f.

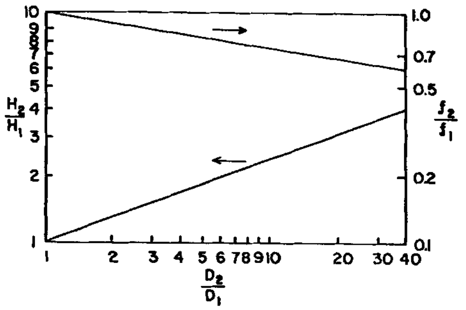

Figure 2. Variation of H_2/H_1 and f_2/f_1 with D_2/D_1.

Suitable baffle plates in design and spacing are provided.

The above procedure has been used to scale up about 65 production columns, all successfully. The largest column in operation is 1.52 m in diameter.

DISCUSSION

As indicated, the optimum agitator speed corresponding to the minimum in the HETS vs. f curve decreases because of increased axial mixing as the diameter increases. A reduced agitator speed also results in a reduced mass transfer coefficient, holdup, and area. However, the reduced mass transfer coefficient, holdup, and area would be expected to be the same as the mass transfer coefficient, holdup, and area in the small diameter test column operating at the same reduced agitator speed because the agitation is relatively uniform and the same over the cross-sectional area of both columns. The difference in actual performance is due to the additional degree of axial mixing in the large diameter column. This is illustrated in Figure 1. As shown, the optimum performance of the production column is at f_2, where HETS is greater than the HETS for the test column.

From the mass transfer performance data in large and small diameter columns, one could deduce the increases in the axial mixing coefficients, provided an assumption is made regarding the relative values of the axial mixing coefficients for the dispersed and continuous phases. This may be the subject of a future paper. In the meantime it is instructive to examine the present scale-up procedure in more detail.

Power Consumption

As shown by Hafez and Baird (1978), the energy consumed is proportional to the cube of the frequency of reciprocation, f, at constant stroke length and plate spacing. Therefore, from Eq. 2

$$\frac{P_2}{P_1} = \frac{P_2/V_2}{P_1/V_1} = \left(\frac{D_1}{D_2}\right)^{0.42} \tag{3}$$

Introducing Eq. 1

$$\frac{P_2/A_2}{P_1/A_1} = \frac{P_2H_2/V_2}{P_1H_1/V_1} = \left(\frac{D_1}{D_2}\right)^{0.42} \cdot \left(\frac{D_2}{D_1}\right)^{0.38} = \left(\frac{D_1}{D_2}\right)^{0.04} \simeq 1 \tag{4}$$

$$\frac{P_2}{A_2} \simeq \frac{P_1}{A_1} \tag{5}$$

Thus the power consumption *per unit of cross-sectional area* is approximately the same for the test column and the production column. Similarly, the power consumption per unit throughput or the energy required per volume fed is approximately the same for the test and production columns. However, the power to the production column is consumed over a greater height of column because the frequency of reciprocation is lower.

Relationship Among Variables

Energy costs have escalated rapidly. Therefore, it is frequently desirable to minimize solvent usage to reduce energy cost for solvent recovery. To do this requires the largest number of stages consistent with good overall economics. A 50 mm dia. test column having 3 m of plate stack will exhibit a large or small number of transfer units or stages, depending on the system. Heights of a theoretical stage can vary form less than 15 cm to more than 1.5 m in relatively rare cases, depending on the system and flow rates. As of now, these wide differences are not predictable from the physical properties of the system alone. That is why it is so important to categorize the system by test work. For now, we shall assume that the 50 mm by 3 m plate stack will provide an optimum number of stages for most applications. Assuming we are to scale up from 50 mm to 2 m in diameter, the height of the production column plate stack will be

$$\left(\frac{2{,}000}{50}\right)^{0.38} \times 3 = 12.2 \text{ m}$$

Figure 2 shows plots of H_2/H_1 vs. D_2/D_1 and f_2/f_1 vs. D_2/D_1 up to ratios of D_2/D_1 of 40. As shwon above and in Figure 2, for a 40-fold increase in diameter or a 1600-fold increase in throughput, the plate stack height will increase by a factor of about 4. For a 10-fold increase in diameter or a 100-fold increase in throughput, the plate stack height will increase by a factor of about 2.4. Similarly, the optimum frequency of reciprocation in the production unit will be 72.4% of that in the test unit for a 10-fold increase in diameter and 59.7% for a 40-fold increase in diameter.

Cost Implications

Let's examine the effect of some conservatism in the scale-up procedure on cost, keeping in mind that some conservatism in process design is usually justified. When the scale-up procedure described is employed, the scaled-up column will always operate substantially below the flood point. Therefore no safety factor on diameter is required. On the other hand, the plate stack height is usually scaled up from optimum performance in the test column. Therefore some design factor on height is justified. Based on our cost experience to date, increasing the height of the plate stack and shell of a column of fixed diameter will increase the cost of the column and drive to about the 0.6 power of plate stack height. Thus, if the plate stack height is increased by 25%, the cost will increase about 14.3%.

NOTATION

A	= cross-sectional area of column
D	= diameter of column
f	= frequency of reciprocation
H	= height of plate stack

HETS	= height of equivalent theoretical stage
P	= power consumed
p	= P/V, power consumed per unit volume
V	= volume of column

Subscripts

1	= test column
2	= production column

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