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Extraction Contactor Performance.

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SUMMARY

A new method of calculating the performance of solvent extraction contactors is presented in its conceptual form. This method is similar to the conventional HETS and HTU methods, developed from the concept of a differential height of column being equivalent to a mixer settler stage with differential efficiency. Some of its implications and advantages are discussed.

INTRODUCTION

The definition of criteria for describing the performance of counter-current solvent extraction devices is a problem which has been encountered in reactor processing since the first improvement on the bismuth phosphate process was contemplated. The three, arbitrarily defined, quantities which have seen application are: the height of a theoretical stage (HETS), the height of a transfer unit (HTU), and, in the case of mixer-settlers, the stage efficiency (defined in various ways).

The stage efficiency, when taken as the number of theoretical stages divided by the number of actual stages is an empirical number of some significance, however, neither the HETS nor the HTU have been entirely satisfactory. The primary difficulty with the HETS concept is that it is based on discrete stages, and is applicable only when the number of stages in operation is large. This is often not the case. The concept of the HTU does not have this disadvantage, being a differential treatment of an operation which is, indeed, of differential character. However, the fundamental assumptions from which the HTU was derived are not applicable to solvent extraction tower calculations. It is assumed that there is an interfacial area which is essentially constant per length of tower, and that the rate of transfer through this area is dependent on diffusion through a stagnant film and proportional to a concentration gradient from the liquid-liquid interface to the body of the liquid. It was originally derived for the absorption of a gas by a liquid where the film could be considered in either the gas or the liquid phase. The decision as to which phase has the controlling film has little physical meaning in an agitated liquid-liquid system, but does determine which of two different numerical values for HTU will be used. A similar anomaly arises in the

concept of a constant interfacial area where the phases are being coalesced and redispersed regularly.

In systems where the mass transfer is accomplished with difficulty, it has been found that the rate of mass transfer is more nearly proportional to the "distance" from equilibrium and the rate of agitation energy input to the system. The development of a differential stage for a differential operation based on this idea will be the object of this work.

It will be assumed that the reader has a working familiarity with the conventional methods of calculating extraction equipment performance. These are well treated in the references cited at the end of this paper.

Theoretical Development

This discussion is restricted to single solute, countercurrent, liquid-liquid solvent extraction with immiscible solvents.

If an aqueous phase, A, of concentration x_i is mixed with a solvent phase, O, of concentration y_i for a very long time, the phases will reach the equilibrium concentrations x_{ei} and y_{ei} . If the operation were continuous

Fig. 1

and A and O were the feed rates of aqueous and organic solvent phases, respectively, it would be conventional to construct an operating line as shown on Figure 1, passing through points (x_i, y_{ei}) and (x_{ei}, y_i) . Now, if the time of mixing is not sufficient to bring the phases to equilibrium the picture becomes more complex, and it becomes necessary to define an efficiency which represents the approach of the system to equilibrium. At once it is obvious from material balance considerations that the point (x_1, y_1) representing the exit concentrations must fall on the line $(y_1 - y_i) = \frac{A}{O} (x_i - x_1)$. Strangely,

this fact is commonly used in batch contacting, but is just as commonly ignored in calculations for continuous multi-stage contactors.

One method for defining efficiency is

$$E = \frac{x_1 - x_i}{x^* - x_i} \quad (\text{wrong}) \quad (1)$$

or its equivalent in terms of y , which does not, one will notice, generally give the same value. Neither of these definitions is fair, because neither the equilibrium concentrations x^* , corresponding to y_1 , nor y^* , corresponding to x_1 , are possible for the system. The efficiency, therefore, should be defined in terms of the limiting condition for the system:

$$E = \frac{x_i - x_1}{x_i - x_{ei}} = \frac{y_1 - y_i}{y_{ei} - y_i} \quad (2)$$

Notice, that the use of this definition requires the knowledge of the relative flow rates of aqueous and organic solvent phases, which is as it should be.

With this definition of efficiency, it is now possible to derive the concept of a differential method based on the equivalent stage.

There is little difficulty in conceiving of a height of extraction tower equivalent to one stage. Why not take any arbitrary length (for the time being smaller than the HETS) and consider it an actual stage with an efficiency other than unity? As this height is decreased indefinitely, a differential condition is approached. It is found that $x_1 - x_i$ becomes

Fig. 2

dx , and E becomes dE , which takes on the new meaning now: the number of theoretical stages found in the increment dl . Equation (2) then becomes

$$(x-x_e)dE = dx, \quad (3)$$

Integrating this from waste to feed concentration, the number of differential states is:

$$\int_{x_w}^{x_f} dE = \int_{x_w}^{x_f} \frac{dx}{x-x_e} = \text{NDS} \quad (4)$$

The difficulty with this, of course, is that x_e is some function of x which has not yet been established. For the establishment of this functional relationship, it is best to return to the type of diagram used in Figure 1, and observe what happens to the geometry of the diagram when the stage efficiency goes to zero. The case will be considered where the operating line has been fixed.

Fig. 3

From Fig. 3 it is seen that x_e occurs at the intersection of the equilibrium line and a line with slope $-A/O$ drawn through the operating line at a point $(x_1 + x_i)/2$, or x_i in the limit. This line will be called the antiop line and will, in application, be a family of parallel lines with x_1 as the parameter. The equation of the operating line is

$$y = \frac{A}{O} (x - x_w) \quad (5)$$

The equation of the antiop line is

$$y - y_i = -\frac{A}{O} (x - x_1), \quad (6)$$

where y_i is evaluated from the operating line equation to give

$$y_i = \frac{A}{O} (x_i - x_w), \quad (7)$$

making the antiop equation become

$$y = -\frac{A}{O} (x + x_w - 2x_1) . \quad (8)$$

If there exists an analytical relation for the equilibrium line, $y = f(x)$, then x_e can be obtained in terms of x_1 by solving

$$f(x_e) = \frac{A}{O} (x_e + x_w - 2x_1). \quad (9)$$

If there does not exist an analytical relation for the operating line, or, if it is too complicated for convenience, a graphical solution can be obtained with little more effort than that required to determine HTU.

The graphical solution involves the use of the distance along the antiop line from the operating line to the equilibrium line, which will be called D_i , and is possible because of the simple geometrical relationship between D_i and $(x_i - x_e)$.

$$x_i - x_e = \frac{D_i}{\sqrt{1 + \left(\frac{A}{O}\right)^2}} \quad (10)$$

The final equation, conducive to graphical solution is, then,

$$\text{NDS} = \int_{x_w}^{x_f} dE = \sqrt{1 + \left(\frac{A}{O}\right)^2} \int_{x_w}^{x_f} \frac{dx}{D_i} \quad (11)$$

Although application of this equation to experimental work is still scanty, it appears that there is a good chance that the height of a differential stage (HDS) will prove at least as good an index of extraction tower performance as the HTU or the HETS.

Implications

Upon study of this method, several points become apparent. The first is that fractions of the differential stage are well defined, and, unlike HETS, calculations are reproducible. Next, it is obvious that there is only one possible number of differential stages as a solution of a given problem, unlike the HTU method which gives at least two. It can be simply shown that when the equilibrium line is straight and the number of theoretical stages equals the number of transfer units, the differential stage method gives the same number of differential stages. It should be noted that although the differential stage method is based on the theoretical stage concept, the number of differential stages will not generally equal the number of theoretical stages when there is a curvature of the equilibrium line.

As a final note, it should be pointed out that the original definition of stage efficiency, which was the major step in the derivation of the method, is directly applicable to mixer-settlers, and will be the same as the overall

efficiency measured in an operation with many stages. And it is interesting to note that a mixer-settler system which uses a large number of stages of small, uniform efficiency actually does approach a differential contactor when analyzed by this method.

NOMENCLATURE

A	Aqueous phase flow rate.
O	Organic solvent phase flow rate.
E	Stage efficiency, or NDS per unit tower height.
D_i	Distance, in graphical solution, from operating line to equilibrium line along antiop line (same units as x and y).
x	Solute concentration in aqueous phase.
x_i	Solute concentration in aqueous phase entering a specific extractor stage.
x_l	Solute concentration in aqueous phase leaving a specific extractor stage.
x_e	Value solute concentration in aqueous phase would reach in a specific stage (i) if equilibrium were attained.
x^*	Solute concentration in aqueous phase in equilibrium with organic solvent phase leaving a stage (i).
y	Solute concentration in organic solvent phase.
y_l, y_i, y_e, y^*	See equivalent values of x .
HDS	Height of differential extraction stage.
HETS	Height of theoretical extraction stage.
HTU	Height of a transfer unit.
NDS	Number of differential stages.

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