Reactor Boiler and Auxiliaries - Course 133

PRINCIPLES OF ISOTOPE SEPARATION

The smallest element of an isotope-separation unit which effects some separation of the process material is called a separating unit. The simplest type of separating unit or stage is one which receives one feed stream and delivers two product streams, one partially enriched in the desired isotope, the other partially depleted. When the degree of separation by a single stage is less than the degree of separation desired between product and waste, it is necessary to connect several stages in series. Such a series-connected group of stages is called a cascade. An example of a cascade is a complete distillation column.

A cascade in which no attempt is made to reprocess the partially depleted product stream (ie, the tails) leaving each stage is called a simple cascade. In a simple cascade, the feed for one stage is the partially enriched product stream (ie, the heads) from the next lower stage in the cascade. (Note: the terms "enriched" and "depleted" in D_2O upgrading work refer to the D_2O content of the D_2O - H_2O mixture.) When partially depleted stage tails have sufficient value to warrant reprocessing, a countercurrent recycle cascade as shown in Fig. 1 may be used. This cascade flow scheme is by far the most common. Such a countercurrent cascade separates F l/hr of feed of composition x_F into P l/hr of product enriched in the desired isotope (D_2 in this case) of composition x_P, and W l/hr of waste, depleted in the desired isotope of composition x_W. The portion of the cascade between the feed point and product end is called the enriching section; the portion between the feed point

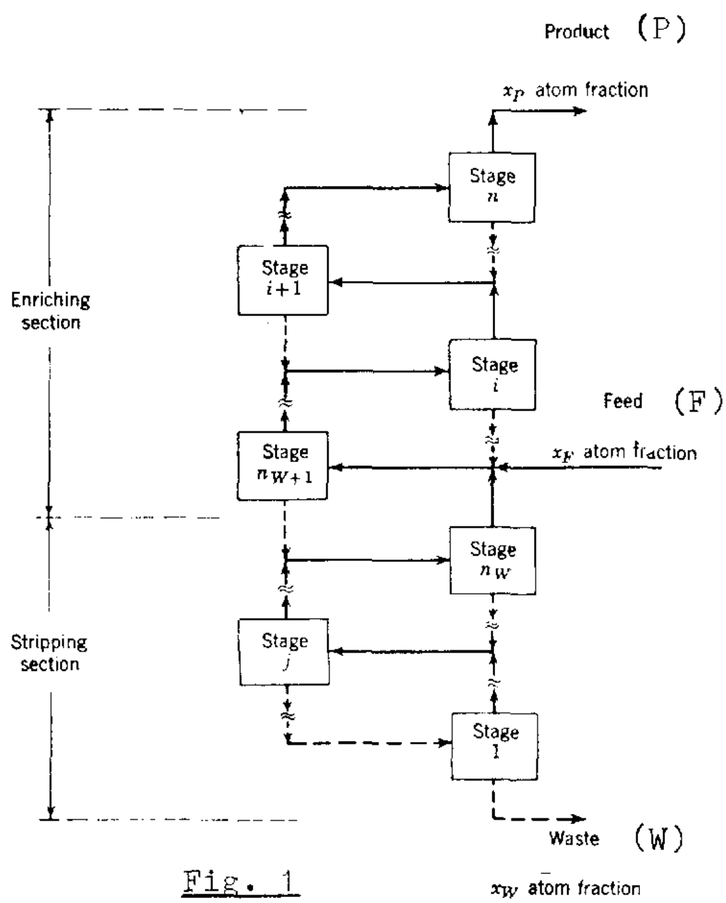

Fig. 1

and waste end is called the <u>stripping section</u>, used to increase the recovery of the desired isotope from the feed. Stages of the cascade are numbered consecutively from 1 at the waste end of the plant to n at the product end. The highest stage of the stripping section is numbered n_W.

General Cascade Equations

In a cascade such as in Fig. 1, feed, product and waste quantities and compositions (the external variables) must satisfy the material-balance equations

$$F = P + W$$

$$Fx_F = Px_P + Wx_W$$

Since there are two equations and six variables, it is possible to specify four external variables independently. For example, these might be product rate and product, feed and waste compositions. In such a case, the other two variables would be given by

Feed rate: $$F = \frac{P(x_P - x_W)}{x_F - x_W}$$

Waste rate: $$W = \frac{P(x_P - x_F)}{x_F - x_W}$$

The number of theoretical stages (n) required to effect a specified separation increases as the over-all separation increases and the separation factor (φ) approaches unity. This number of stages (or transfer units) is given by the equation

$$n = \frac{2 \ln \left(\frac{x_P (1 - x_F)}{x_F (1 - x_P)} \right)}{\ln \varphi} - 1$$

twice the theoretical minimum at total reflux.

If G and L are the quantities of gas (vapour) and liquid flowing up and down a column respectively, then the reflux ratio is given by

$$v = \frac{L}{G - L}$$

When the column is operating on total reflux, v approaches ∞, since the amount of vapour flowing up the column is equal to the amount of liquid flowing down. The quantity of liquid flowing down, which at the high reflux ratios usually used, is about equal to the quantity of gas, determines the cross-section of the column, while the number of stages (n) determines its length. The product nv is proportional to the volume of the column and has a minimum value for which the column will usually be designed.

If γ is assumed to be constant for each stage (ie, if the pressure drop through the column is assumed to be zero) and to be equal to the average value in a distillation column, the actual number of plates needed for a given enrichment may be calculated from

$$\text{Enrichment} = \gamma_{AVG}^{\;nE}$$

where E is the average plate efficiency, and the enrichment is the ratio of atom fractions of D_2O in bottoms to tops product.

Examples

1. Calculate the feed and waste rates (in l/hr) which would be obtained at equilibrium using a distillation column capable of processing 90% D_2O feed into 3.9 l/hr of 99.8% D_2O product and a waste composition of 25% D_2O.

   Solution: Using the material-balance relations, the feed rate is given by:

$$F = \frac{P\ (x_P - x_W)}{x_F - x_W}$$

$$= \frac{3.9\ (0.998 - 0.25)}{0.90 - 0.25}$$

$$= \underline{\underline{4.5\ \text{l/hr}}}$$

   Similarly, the waste rate is given by

$$W = \frac{P\ (x_P - x_F)}{x_F - x_W}$$

$$= \frac{3.9\ (0.998 - 0.90)}{0.90 - 0.25}$$

$$= \underline{\underline{0.6\ l/hr}}$$

2. Estimate the number of stages required in an electrolytic cascade to upgrade a 50 wt. % D_2O feed to 99.8 wt. % D_2O (Assume: γ = 10).

<u>Solution</u>: The number of stages required is given by

$$n = \frac{2 \ln \left(\frac{x_P\ (1 - x_F)}{x_F\ (1 - x_P)} \right)}{\ln \gamma} - 1$$

$$= \frac{2 \ln \left(\frac{0.998\ (1 - 0.50)}{0.50\ (1 - 0.998)} \right)}{\ln 10} - 1$$

$$= 4.4$$

$$\approx \underline{\underline{5 \text{ stages}}}$$

NOTE: An integral number of stages must be used. Since 4 stages would be inadequate, 5 stages would be required.

3. Estimate the theoretical equivalent number of stages in the Douglas Point Sulzer packed distillation column, assuming:

$$\gamma = 1.05$$

$$x_F = 0.90$$

$$x_P = 0.998$$

3. Why are more stages than this required in practice?

Solution:

$$n = \frac{2 \ln \left(\frac{x_P \ (1 - x_F)}{x_F \ (1 - x_P)} \right) - 1}{\ln \gamma}$$

$$= \frac{2 \ln \left(\frac{0.998 \ (1 - 0.90)}{0.90 \ (1 - 0.998)} \right) - 1}{\ln 1.05}$$

$$= \underline{\underline{164 \text{ stages}}}$$

The above calculates the equivalent theoretical number of stages, assuming each stage to be 100% efficient. In practice, stage efficiencies are less than 100% efficient, and in the above example, about 280 equivalent stages would be required, assuming typically 60% stage efficiency.

ASSIGNMENT

1. State what is meant by a stage, a simple cascade and a recycle cascade as applied to isotope separation.
2. Write down the general material-balance equations, and indicate the meaning of each symbol used.
3. What is the reflux ratio and what is meant by total reflux?
4. Estimate the number of plates required in a distillation column to effect an H_2O - D_2O separation into 1% D_2O tops and 95% D_2O bottoms, if the plates are 50% efficient and the average stage separation factor is 1.05.

R. Popple