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ENERGY-SAVING TECHNOLOGY OF MASS TRANSFER IN TRAY COLUMNS WITH SEPARATE PHASE MOVEMENT

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Abstract

The costs for industrial processes of separation in tray columns, both capital and current, are inverse to efficiency of the mass transfer between vapor (gas) and liquid. For such type of equipment the separation efficiency improvement potential in related to organization of phase movement in the column.

The most efficient component separation is achieved upon perfect displacement by liquid and vapor. By means of the customary technological regimes and contact devices it seems impossible to reach the desired result. But this problem can be solved by the mass exchange technology with separate phase movement (cyclic process), implemented as follows: lack of outflow of liquids to the trays vapor admission; lack of mixing of liquids in adjacent trays upon outflow of liquid. The perfect displacement effect is achieved by means of using of the coordinate system for changing of concentration of the volatile component on contact stage during the vapor supply. It allows actually eliminating the mixture of liquid in the tray with various concentrations of high-volatile component. The mathematic modeling allowed offering theoretical stage model with perfect displacement with a trayed column for description of the mass transfer process with separate phase movement. Meanwhile analytically it was proved that the existing theoretical tray and perfect displacement theoretical tray are two extreme cases of hydrodynamic mass transfer regimes in the trays – perfect mixing and perfect displacement. Theoretical developments were implemented in special contact devices patented in numerous countries. Industrial implementation was held in Ukraine in food alcohol production. The first industrial column has been in operation for 4 years already. The tests showed the component separation efficiency improvement by 3 to 4 times, while the process power consumption reduced 1.5 to 2 times.

Keywords:

Mass transfer, cyclic distillation, theoretical stage, the theoretical stage model with perfect displacement

INTRODUCTION

The comparison of formalized models, describing the operation of mass transfer column devices allows determining the type of equipment with the lowest power consumption in processes. For tray columns, the most widespread model is the model of theoretical contact phase, offered by McCabe-Thiele [1]. This model is based on the column material balance by distributed component and can be summarized in two postulates.

1. The concentration of volatile component in the contact phase is constant. 2. Vapor removing from the phase is in balance with liquid leaving the phase. In this case, the hydrodynamic indices of liquid and vapor flows are reduced to the perfect mixing models. The use of combinations of the other hydrodynamic models for liquid and vapor phases allowed Lewis to draw conclusions on significant enhancement of component separation. The greatest effect is achieved upon perfect displacement by vapor and liquid and single-direction movement of liquid in adjacent contact phases. All subsequent studies in this segment were aimed at industrial implementation of W.K. Lewis' [2] conclusions. In particular, M.R. Cannon [3] suggested the following phase interaction mode. While the vapor passes through the column, the liquid doesn't flow from tray to tray, and if the liquid overflows, it is not mixed on adjacent trays. The aim of the present paper is to determine the correlation between all offered models from the prospective of energy consumption during the separation process.

COMPARISON OF PHASE INTERACTION MODES

Upon description of distribution the concentration of volatile component (VC) on the contact stage operating in the mode of separate phase movement (cyclic mode), there is used an equalizing of material balance in differential mode. The change of VC amount in Hdx_n liquid is equal to change of VC amount in $Gd\tau(y_n - y_{n-1})$ vapor, or

$$\frac{dx_n}{d\tau} = -\frac{G}{H}(y_n - y_{n-1}) \quad (1)$$

where H - is the amount of liquid on the tray, *mol*; G - is vapor consumption, *mol/s*; y_n - VC concentration in vapor at the output from tray, %; y_{n-1} - is VC concentration in vapor at input to the tray, %; x_n - is VC concentration in liquid on the tray, %; τ - is the vapor supply time, s; and n - is the tray number.

The perfect hydrodynamic mode of liquid overflow from one tray to another is described with the following balance $x_n(0) = x_{n+1}(\tau_v)$, where τ_v - is the vapor supply time, s.

Let's consider the cyclic and stationary processes from the single point of view, namely the time of mass transfer on the tray. For the cyclic process, the mass transfer time coincides with vapor supply time τ_v . For the stationary process of perfect displacement, the change of the concentration is related to the time of liquid movement about the tray or to the substantial produced concentration.

$$\frac{dx_n}{d\tau} = \frac{\partial x_n}{\partial t} v_l, \quad (2)$$

where v_l - is the liquid flow rate about the tray, *m/s*;

Upon change of the VC concentration on the standard process tray there is used a differential equation of material balance of elementary volume of the liquid layer.

$$\frac{dx_n}{dt} = -\frac{G}{Ll_T}(y_n - y_{n-1}), \quad (3)$$

where l_T – is the length of the tray operative part, m; L – is the liquid discharge, mol/s. By placing (3) into (2), we receive

$$\frac{Dx_n}{D\tau} = -\frac{G}{L\bar{\tau}}(y_n - y_{n-1}), \quad (4)$$

where $\bar{\tau} = \frac{l_T}{v_l}$ – is the time of stay of the liquid on the tray, s.

In view of the fact that the amount of liquid on the tray H upon instant overflow may be recorded as $H = L\tau_v$, equation (1) will look as follows:

$$\frac{dx}{d\tau} = -\frac{G}{L\tau_v}(y_n - y_{n-1}) \quad (5)$$

Therefore, the cyclic and stationary processes are described with similar material balance equations (4) and (5), according to the nature of vapor and liquid interaction $y_n(x_n) \rightarrow x_{n+1}$ we determine that the cyclic process is similar to the stationary one upon single-direction movement of liquid on adjacent contact phases and perfect displacement by liquid and vapor.

MATHEMATIC MODEL OF THE COLUMN WITH SEPARATE PHASE MOVEMENT

The formalized model of the column operating in the cyclic mode may be represented with following equations.

1. Material balance by volatile component on the contact phase upon vapor submission, $\frac{dx_n}{d\tau} = -\frac{G}{H}(y_n - y_{n-1})$;
2. Liquid hydrodynamics upon overflow from one tray to another: $x_n(0) = x_{n+1}(\tau_v)$;
3. Mass transfer kinetics: vapor leaving the tray reaches the equilibrium with liquid remaining on the tray;
4. The equilibrium dependency is of linear nature: $y^* = mx$;

The suggested system of equations shall be solved analytically. Generally, the concentration profiles at each phase shall be written down as follows:

$$x_n(\tau) = e^{-\frac{Gm}{H}\tau} \sum_{i=1}^n C_i \frac{(\frac{Gm}{H}\tau)^{n-1}}{(n-i)!}, \quad i = \overline{1, n} \quad (6)$$

OPERATING LINES

For all mass transfer devices the dependency between concentrations of distributed liquid in phases $y = f(x)$ in any column section is depicted with a line called the process operating line. By solving the material balance equation by distributed component as against y we receive the following:

$$y = \frac{L}{G} (x - x_0) + y_0. \quad (7)$$

Equation (7) is true upon consideration of the material balance and for the cyclic mode in one cycle:

$$G\tau_v \frac{1}{\tau_v} \int_0^{\tau_v} y(\tau) d\tau + Hx_0 = G\tau_v \frac{1}{\tau_v} \int_0^{\tau_v} y_0(\tau) d\tau + Hx \quad (8)$$

In view of the fact, that

$$\bar{y} = \frac{1}{\tau_v} \int_0^{\tau_v} y(\tau) d\tau$$

$$\bar{y}_0 = \frac{1}{\tau_v} \int_0^{\tau_v} y_0(\tau) d\tau \quad \text{and} \quad H = L\tau_v, \text{ we receive}$$

$$\bar{y} = \frac{L}{G} (x - x_0) + \bar{y}_0 \quad (9)$$

where \bar{y}_0 – is the average VC concentration in vapor entering the column, % ; \bar{y} – is the average VC concentration in vapor leaving the column, %.

For tray column apparatus the model of theoretical stage determines the concentrations of distributed component on each tray. Meanwhile the operating line is discrete and coordinates of points (trays) of the operating lines in $Y - X$ coordinates shall be recorded as $A(x_n, y_{n-1})$, (fig.2).

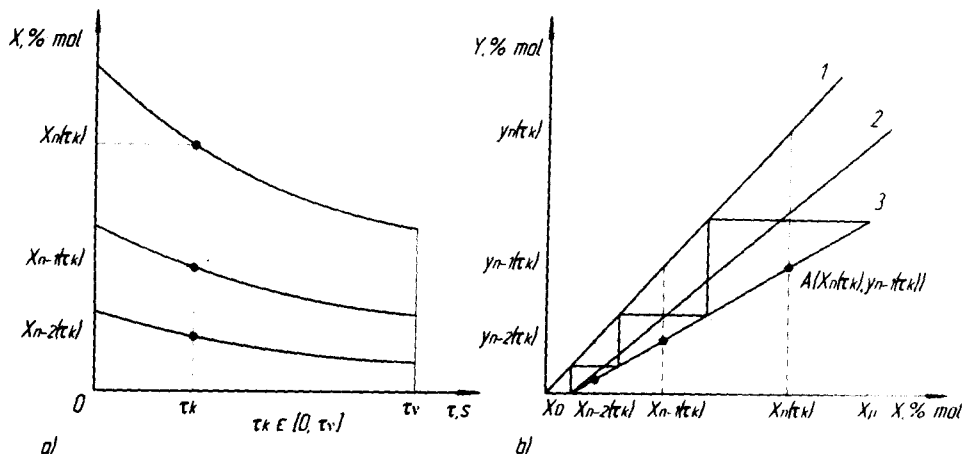


Figure 1: The methodology of construction of the perfect displacement mode operating line is as follows: a) Temporary concentration profiles in liquid; b) Depicting of the perfect displacement operating line in $Y - X$ coordinates; 1 – equilibrium line; 2 – perfect mixing operating line; 3 – perfect displacement operating line.

We use this method for obtaining of the cyclic process operating line. For random moment of time $\tau_k \in [0, \tau_v]$, on all trays we determine the coordinates of the operating line point as $A[x_n(\tau_k), y_{n-1}(\tau_k)]$, (fig.1). By changing the moments of time $\tau_k \in [0, \tau_v]$, we find graphically any number of points belonging to the operating line (fig.1, line 3).

Therefore, the operating line of the cyclic process is built on the basis of differential equation of the material balance by the distributed component on contact phases. It is drawn by definition as a line of points of encounter of vapor rising from the below tray with liquid located on the above tray. This line is continuous and straight for $y^* = mx$. The tangent of the operating line decline corner is less than L/G values.

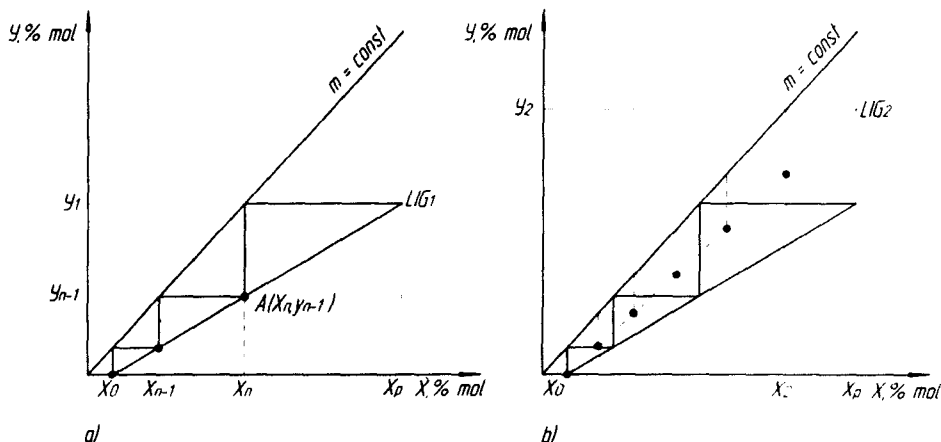


Figure 2: Matching of power consumption for separation in $Y - X$ coordinates
 a) theoretical stage model; b) the theoretical stage model with perfect displacement

Using this line one may determine the values of concentration of the distributed component in vapor and liquid for each tray and any vapor supply moment. The contact phase built on this line may be called a theoretical contact phase of perfect displacement, for its operating conditions fully correspond to the conditions of hydrodynamic regime of perfect displacement by liquid and vapor upon single-direction movement of liquid about the adjacent trays offered by Lewis. The difference between cyclic and stationary process consists in alteration of the coordinate system upon separation. For the cyclic process – during the vapor supply $\frac{dx_n}{dt}$, for the stationary process – along the route of liquid about the tray $\frac{dx_n}{dt}$.

THE INFLUENCE OF HYDRODYNAMIC MODELS OF PROCESS INTERACTION ON POWER CONSUMPTION UPON SEPARATION

Upon determination of the qualitative side of influence of the hydrodynamic models of phase interaction on power consumption upon separation, let's consider the models of theoretical stage and theoretical stage with perfect displacement for columns with equal number of trays, equal separation degree of the distributed component and equal liquid flows (fig.2). In this case the alteration of concentration of the distributed component in each phase will be equal for both models, but in the first case (theoretical stage) the alteration shall take place on the discrete basis and in the second case (theoretical stage with perfect displacement) on the continuous basis.

The vapor leaving the column in the first case has the concentration of y_1 upon vapor discharge of G_1 , and in the second case from the first tray rises the vapor with average concentration of the distributed component y_2 , upon vapor discharge G_2 . From the material balance on the distributed component it follows that (fig.2)

$$L(x_p - x_0) = G_1 y_1 \text{ and } L(x_p - x_0) = G_2 y_2, \text{ or } G_1 y_1 = G_2 y_2.$$

Therefore, the vapor discharge for separation is inverse to the concentration of volatile component in vapor rising from the column $\frac{G_1}{G_2} = \frac{y_2}{y_1}$. Upon equal vapor discharge (fig.2) the separation efficiency in the theoretical stage model with perfect displacement (3 trays) significantly exceeds the theoretical stage model (6 trays).

CONCLUSION

In actual conditions of operating of overflow trays, the attainment of perfect displacement mode by vapor and liquid is related to some difficulties. For the mass transfer technology with separate phase movement a significant part of the problems is solved automatically due to the use of the temporal coordinate system. The actual calculation of apparatuses may be performed using two parameters. 1. The mass transfer kinetics is determined by local efficiency not exceeding 100%. 2. The hydrodynamics of liquid flow is described using a part of liquid flowing from one tray to another. Both these parameters are reflected in the process operating lines. Besides, as far as the operating line is uninterrupted, the equilibrium line shape influences on separation efficiency.

All theoretical conclusions were implemented in industry with new contact devices in tray column apparatuses upon production of food alcohol.

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