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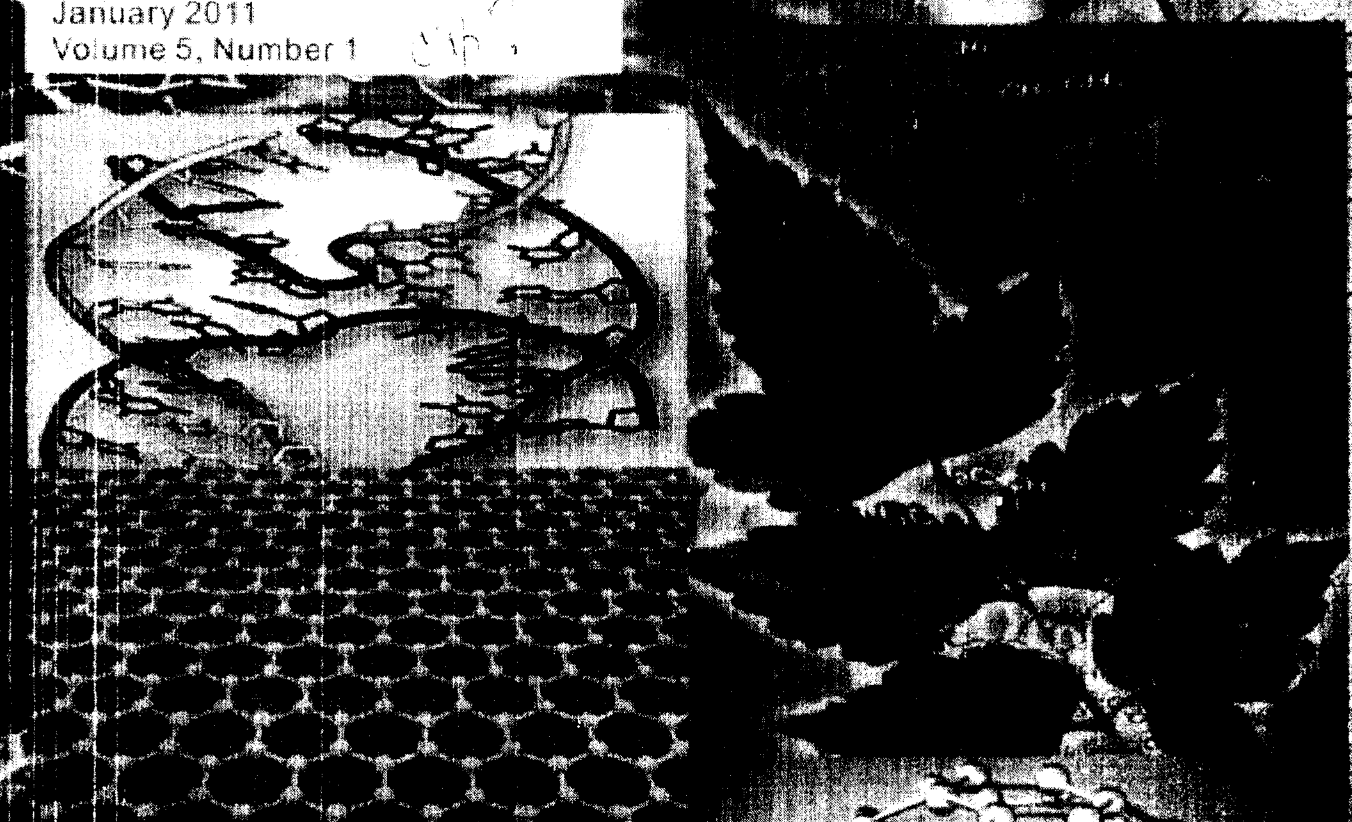

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Hydrodynamics of Liquid Flow in the Model of Theoretical Stage with Perfect Displacement

Volodymyr Maleta[1], Vitaliy Taran[2] and Bogdan Maleta[2]

1. Maleta Cyclic Distillation LLC, Ukraine

2. Department of Machines and Equipment, National University of Food Technologies, Kiev, Ukraine

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Abstract: For the cyclic process of mass transfer in tray columns there are considered the hydrodynamic models of liquid flow during steam supply and during overflow of liquid from tray to tray. During steam supply, the hydrodynamic model is determined as perfect displacement model, and during liquid overflow, it is described as cell model. There were received the characteristics of liquid flow as follows: average residence time of liquid, degree of dispersion around the mean on the tray, number of perfect mixing cells depending on multiplication factor of exchange of liquid delay. In Y-X coordinates there is depicted a work line and theoretical stage of perfect displacement model. There were considered the conditions of mutual transfer of theoretical stage and theoretical stage with perfect displacement. The advantages of the mass transfer cyclic process to the stationary one are stated.

Keywords: mass transfer, cyclic distillation, theoretical stage, the theoretical stage model with perfect displacement, residence time

1. Introduction

Pursuant to Lewis' work [1], the use of combinations of various hydrodynamic models of liquid and vapor phases enhances the efficiency of component separation on the tray. The greatest effect is achieved upon perfect displacement by liquid and vapor and sing-direction movement of liquid on adjacent contact degrees. In such conditions the efficiency of Murphy's tray may significantly exceed the local efficiency and reach 200-300%. Cannon [2] suggested the way of phase interaction, for which during the passage of vapor through the column the liquid doesn't overflow from tray to tray and upon liquid overflow it doesn't mix on adjacent trays (cyclic process). In a series of works [3, 4] it was shown that upon comparison of stationary and cyclic processes both by the time of mass transfer on the tray and by the phase interaction nature, the cyclic process is similar to the stationary

Corresponding author: Volodymyr Maleta, Ph.D., research fields: mass transfer and distillation process. E-mail: vmmaleta@gmail.com.

process upon single-direction movement of liquid on adjacent contact levels and perfect displacement by liquid and vapor. A mathematical model of the hydrodynamic processes occurring in a periodic cycled plate column is developed and experimentally confirmed. The model is applied to the prediction of the holdup distribution and the investigation of hydrodynamic problems [5]. For description of mass transfer upon perfect hydrodynamic displacement processes in coordinates Y-X there was suggested the theoretical stage model with perfect displacement [6]. The model shows dynamic change of composition of the contacting phases for any vapor supply moment on all column trays and is based on differential equation of material balance as the point of meeting of the vapor raising from the below tray and liquid on the above tray. The objective of the present work is the mathematic modeling of the liquid flow hydrodynamics in tray columns with separate phase movement.

2. Peculiarities of Hydrodynamic Conditions of Work of the Tray Columns with Separate Phase Movement

The mass transfer technology suggested by Cannon in the first attempts of industrial implementation used the ordinary overflow trays accompanied by changeable, or cyclic supply of contacting phases to the column. Their use was unsuccessful. Subsequently the creation of special contact devices allowed obtaining a broad range of the required technical solutions with various options of discrete and even uninterrupted flow inputs. Therefore, in our opinion, the term o separate phase movement reflects the essence of this phenomenon in the most integral manner and may be used as a synonym to the term of the cyclic process. In essence, the cyclic process of mass transfer in tray columns comes to satisfaction of requirements to the liquid flow dynamics: (1) lack of the liquid overflow on the trays during vapor supply; (2) lack of mixing of liquids on adjacent trays during liquid overflow. The constructive solution of such tasks automatically brings about the enhancement of mass transfer efficiency and reduction of power consumption for distillation process. The authors obtained a series of patents, which allowed implementing all advantages of cyclic process in industrial field. The algorithm of engineering design of a special tray is as follows. The requirement as to the lack of liquid overflow on the trays during vapor supply is performed on the trays of hollow type while the vapor speed exceeds the column flood speed. The requirement as to the lack of liquid mixing on adjacent trays during liquid overflow is performed by means of a sluice chamber located under the tray. This installation works as follows. The liquid flows (supply, phlegm) are continuously supplied to the tray. During vapor supply, the liquid doesn't overflow from tray to tray for the speed of vapor is the column exceeds the column flood speed. The controlling influence on liquid overflow from tray to tray is exercised by vapor, the cut in supply of which for a couple of seconds allows the liquid to overflow from the tray bubbled cloth to the sluice chamber. Subsequent vapor supply opens the sluice chamber and the liquid flows to the empty tray below. Such sequence of actions takes place synchronically on all trays on the column height. The number of trays in the columns consecutively increased from 5 to 21. No complication in provision of column operability related to the increase of tray number was observed. Description of the liquid flow hydrodynamics should be subdivided in two stages–vapor supply stage and liquid overflow stage. In the first case during the mass transfer between vapor and liquid, the liquid is on the bubbles cloth of the tray and doesn't overflow from tray to tray. We disregard the transfer of liquid to the above tray. The volume of liquid on the tray can be considered as closed-circuit. No particle of liquid will leave this volume. And though the liquid inside the volume is perfectly mixed under the influence of vapor flow, we have equal speed of movement of the liquid volume, which equals to zero, lack of gradient in concentrations and temperatures for a certain point of time and, finally, equal time of stay of the liquid particles on the tray. Such conditions are peculiar of only one hydrodynamic mode, i.e., perfect displacement mode. Meanwhile it can be achieved in actual circumstances, and not only in hypothetic piston-flow. Therefore, during transfer of vapor about the column, the hydrodynamic model of liquid flow on the tray in real circumstances is the perfect displacement model.

3. The Theoretical Stage Model with Perfect Displacement

For formalized description of work of the tray columns with separate phase movement the mathematic model of the process including the following equations is used.

(1) Material balance by volatile component VC on the contact stage during vapor supply:

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

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.

(2) Liquid flow hydrodynamics during liquid overflow from tray to tray:

$$x_n(0) = Fx_{n+1}(\tau_v) + (1-F)x_n(\tau_v) \qquad (2)$$

$$0 < F \leq 1,,$$

where F - is the multiplication factor of transfer of liquid delay, $F = H_l / H$;

H_l -is the amount of liquid flowing from the tray, mol.

τ_v -is the vapor supply time, sec.

(3) Mass transfer kinetics:

Vapor leaving the tray achieves balance with liquid remaining on the tray;

(4) Equilibrium line:

$$y^* = mx \qquad (3)$$

The suggested system of equations is solved analytically. Generally, the concentration profiles on each stage are recorded as follows:

$$x_n(\tau) = e^{-\frac{Gm}{H}\tau} \sum_{i=1}^{n} C_i \frac{\left(\frac{Gm}{H}\tau\right)^{n-i}}{(n-i)!}, i = \overline{1,n} \qquad (4)$$

Meanwhile the source conditions are as follows:

$$x_i(0) = C_i$$

For tray columns, the most widespread model is the model of theoretical stage offered by McCabe-Thiele [1]. The model is based on the column material balance by distributed component and is expressed in two postulates as follows: (1) The concentration of volatile component on the contact stage is permanent; (2) Vapor leaving the stage is in balance with liquid leaving this stage. In this case, the hydrodynamic models of liquid and vapor flows are expressed as perfect mixing models. The process operating line determines the concentrations of distributed component in liquid and vapor on each tray. Meanwhile, it is discrete and the coordinates of operating line points (trays) in $Y - X$ coordinates are recorded as $A(x_n, y_{n-1})$.

We use this technique for obtaining of the cyclic process operating line. Upon known interim concentration profiles in liquid and vapor for a random point of time $\tau_k \in [0, \tau_v]$, on all trays we determine the operating line point coordinates as $A[x_n(\tau_k), y_{n-1}(\tau_k)]$, (Fig. 1). By changing the time points $\tau_k \in [0, \tau_v]$, we graphically find any number of points referred to the operating line (line 3, Fig. 1). Therefore, the operating line of the cyclic process is built on the basis of differential equation of the material balance by distributed component on the contact stages. It is drawn by definition as a line of points of meeting of the vapor rising from the below tray and liquid located on the above tray. The line is uninterrupted and straight for $y^* = mx$. The tangent of the perfect displacement operating line inclination is less than the values of

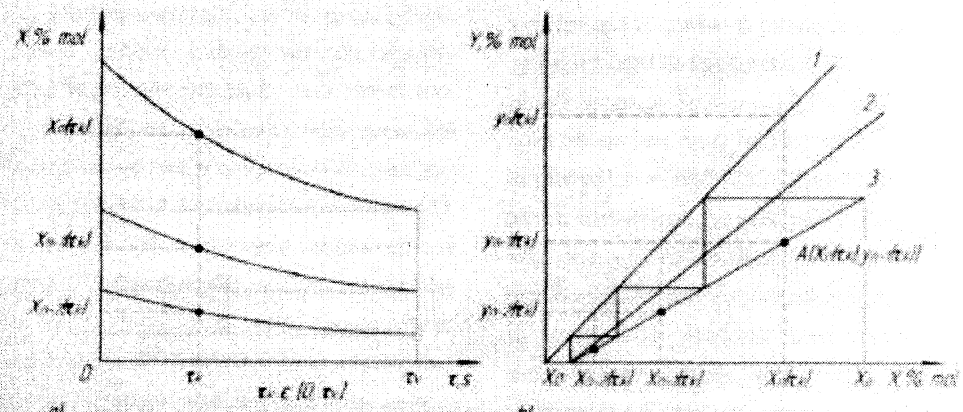

Fig. 1 The methodology of construction of the perfect displacement mode operating line is as follows: a) Temporary concentration profiles in liquid; b) Depicting of the perfect displacement operating line in Y-X coordinates: 1 equilibrium line; 2 perfect mixing operating line; 3 perfect displacement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

L/G. Using this line, one can determine the values of concentration of the distributed component in vapor and liquid for each tray and any vapor supply point of time. The contact stage built on this line may be called a theoretical contact stage of perfect displacement, for its operation conditions are the same as those of the hydrodynamic mode of perfect displacement of liquid and vapor in a single-direction liquid movement on adjacent trays suggested by Lewis. The difference between cyclic and stationary process consists in change of the coordinate system upon distillation. For cyclic process–during vapor supply $dx_n/d\tau$, for stationary process–along the liquid movement route on the tray dx_n/dl.

4. Hydrodynamic Model of Liquid Flow upon Liquid over flow from Tray to Tray

In the previous section upon construction of theoretical stage of perfect displacement we considered the case of the lack of liquid mixing on adjacent trays, F=1. According to the theoretical stage model with perfect displacement, the liquid flow hydrodynamics upon overflow results in distribution of components on contact stages as of the commencement of vapor supply, equation (2), or, in other words, in determination of constants of C_i in equation (4). Therefore, the task of description of imperfect flows is simplified significantly. We use the simplest, historically the first cell model, the only parameter in which is the number of cells. To determine the actual stage of liquid mixing, we need to study the distribution of separate liquid particles according to the time of their stay on the tray, i.e., to determine what share of the flow is on the tray in a certain point of time. The data on distribution of the time of stay of separate particles on the tray are obtained by depicting of the source system disturbance (tracer agent input) and analysis of curves of dependence of the tracer agent concentration on time $C(\tau)$ in output liquid. For the mixing degree analysis we use three values:

The average residence time of liquid

$$\bar{\tau} = \frac{\int_0^\infty \tau c(\tau) d\tau}{\int_0^\infty c(\tau) d\tau} \quad (5)$$

The degree of dispersion around the mean

$$\sigma^2 = \frac{\int_0^\infty \tau^2 c(\tau) d\tau}{\bar{\tau}^2 \int_0^\infty c(\tau) d\tau} - 1, \quad (6)$$

The hydrodynamic cell model

$$N = \frac{1}{\sigma^2}, \quad (7)$$

Modeling of the liquid flow hydrodynamics in the range of $0 < F \le 1$, allowed obtaining the following dependences:

The average residence time of liquid

$$\bar{\tau} = \frac{\tau_s}{F}, \quad (8)$$

The degree of dispersion around the mean

$$\sigma^2 = 1 - F, \quad (9)$$

The hydrodynamic cell model

$$N = \frac{1}{1-F}, \quad (10)$$

One can determine the authenticity of obtained dependences of essence of the cell model of the liquid flow hydrodynamics by studying their behavior upon extreme values of F. If $F = 1$, the average time of stay $\bar{\tau}$ is equal to the vapor supply time, the dispersion is $\sigma^2 = 0$, and the number of cells is $N \to \infty$, and these are the perfect displacement conditions. Similarly, upon $F = 0$, the average time of stay is $\bar{\tau} \to \infty$, the dispersion is $\sigma^2 = 1$, and the number of cells is $N = 1$ -which are the perfect mixing conditions. It is considered that while the number of cells is $N \ge 10$, the mode approximates to the perfect displacement. In our case, this condition is met by the range $0.9 < F \le 1$. Therefore, the liquid flow hydrodynamics determines the theoretical stage: from the theoretical stage with perfect mixing to the theoretical stage of perfect displacement. For the cyclic mode the physical interpretation of transfer of the theoretical stage with perfect displacement into the theoretical stage model results in increase of the amount of liquid on the tray up to infinity, $H \to \infty$, and in this case the concentration of volatile component on the tray during the vapor supply time will not change.

5. Conclusions

The offered mass transfer mode has some features that compare it favorably with the steady one. Separation efficiency does not depend on the string diameter. The load increase of a column on a liquid does not lead to an increase in hydraulic resistance and string blocking, as the quantity of a liquid on a plate remains constant, and cycle frequency is changed only. The effect of secondary self-evaporation of a liquid is observed. Gas content of the bubble layer is on the increase. Residence time of a liquid in a string decreases. Besides, mass transfer technology with separate movement of phases has more degrees of freedom in the process control.

The introduction of this mass transfer mode on the industrial basis can provide a considerable economic effect in the following respects:

- Capital expenditure saving;
- Current energy saving;
- Increase in product's quality;
- Increase in product's yield;
- Environment enhancement.

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