In an ideal cascade the regime of operation of one part of the cascade has little effect on the process in the other part. As a result, there is very little shift in the "zero" point. This enables us to carry out the transition process in a regime with product and waste outlets disconnected. When either of them is connected, we observe the same features as in cascades without stripping part.

NOTATION

ρ, step delay; L, flow between stages; $c = c(s, t)$, concentration of extracted isotope at the s-th stage at time t; ε = coefficient of enrichment of a stage; P, product flow (extraction); W, waste flow; F, input flow; c_P, concentration at product point; c_W, concentration at waste point; c_F, input concentration; c^*, concentration at "junction" point between sections; c_f, concentration at input points; l_W, number of stages in stripping part of the cascade (in units of εs); l_P, number of stages in the cascade (in units of εs); E_i, inventory of i-th phase-reversal device; N, number of sections in the cascade.

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THEORY OF THERMODIFFUSION SEPARATION ACCORDING TO THE FRAZIER SCHEME

G. D. Rabinovich

UDC 621.039.3

A theory of a thermodiffusion column with transverse sampling streams is given on the basis of the transport equation for a binary mixture.

Among the different kinds of thermodiffusion apparatus of continuous action, the scheme proposed by D. Frazier in 1958 to connect thermodiffusion columns in which the sampling streams do not pass through but move outside the columns occupies a special place.

The delivery of the supply σ_e and σ_i with concentrations c_0 is accomplished at the upper and lower ends in a plane thermodiffusion column with gap δ, height L, and length B (Fig. 1), where both streams can have the same (Fig. 1a) and opposite (Fig. 1b) directions. Sampling of the product is carried out at the ends opposite to the supply entrance.

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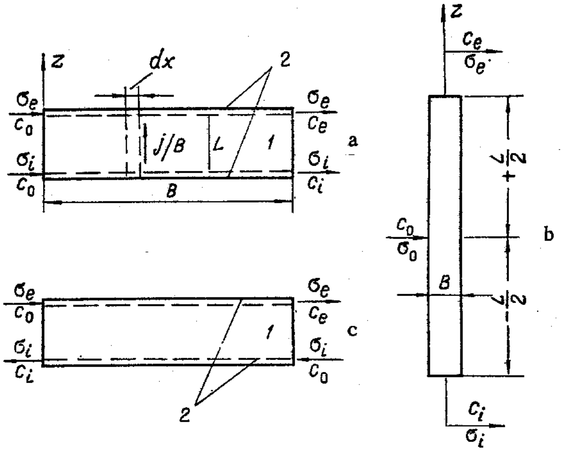

Fig. 1. Diagrams of a column with transverse streams in a direct (a) and countercurrent (b) flow [1) separating part of the column; 2) channels]; c) diagram of a column with a central feed.

Frazier gave a theory of this process in [2] in application to fractionation of petroleum products, which was constructed on the basis of simplified model representations, in which connection the dependences obtained are approximate and make difficult an exact quantitative estimation of the advantages of the scheme under consideration.

An analytic description of the operation of the Frazier scheme is given in this paper on the basis of a general theory of thermodiffusion columns for a binary mixture [3] under the following assumptions:

1) Ideal mixing of the streams σ_e and σ_i with the stream j proceeding from the separating part of the thermodiffusion apparatus occurs in the vertical direction in the lower and upper channels.
2) Diffusion along the x axis within the separating part of the apparatus is neglected. This condition should be satisfied completely satisfactorily for a sufficiently large number of discrete columns, each of which has a dimension along the axis which is much less than the total length B.
3) Diffusion in the upper and lower channels is neglected. The condition governing the applicability of this assumption is considered below [see (40)].
4) The concentration of the target component is low everywhere ($c \ll 1$).

The transfer in the z direction in any vertical section of the column under consideration is determined by the expression

$$j = H\left(c - \frac{dc}{dy}\right). \tag{1}$$

Since we consider the stationary state, then div j = 0 and we obtain

$$\frac{d^2c}{dy^2} - \frac{dc}{dy} = 0. \tag{2}$$

The solution of (2) is

$$c = A_1(\xi) + A_2(\xi)e^y, \tag{3}$$

where the coefficients A_1 and A_2 are functions of the dimensionless coordinate

$$\xi = \frac{x}{B}. \tag{4}$$

Now let us examine column sections of length dx (Fig. 1a). The flux j per unit length of the column is j/B. Mixing of this stream with the stream σ_e in a section dx at the upper end of the column results in a rise in concentration dc in this section; i. e.,

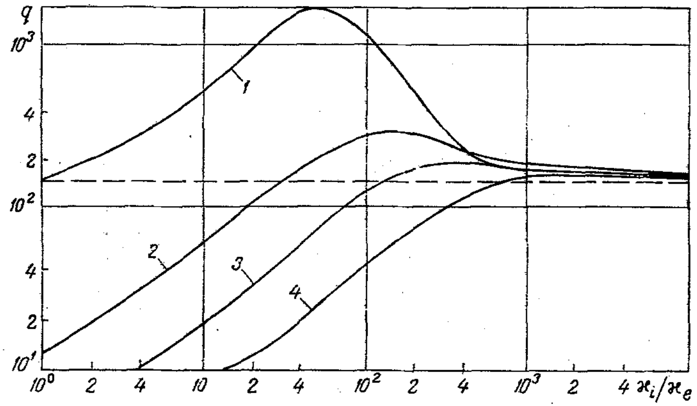

Fig. 2. Dependence of the degree of separation on the ratio $\varkappa_i/\varkappa_e$ for $y_e = 5$: 1) $\varkappa_i = 0.2$; 2) 0.5; 3) 1.0; 4) 2.5. The dashed line corresponds to the degree of separation in an ordinary column without sampling.

$$\frac{jdx}{B\sigma_e} = dc. \tag{5}$$

At the lower end of the column we have, analogously,

$$\frac{jdx}{B\sigma_i} = -dc. \tag{6}$$

Replacing the magnitude of the stream in (5) and (6) by its value from (1) and introducing the notation

$$\frac{\sigma_e}{H} = \varkappa_e, \quad \frac{\sigma_i}{H} = \varkappa_i \tag{7}$$

we obtain the condition which the coefficients A_1 and A_2 in (3) should satisfy:

$$\left.\frac{dc}{d\xi}\right|_{y=y_e} = \frac{1}{\varkappa_e}\left(c - \frac{dc}{dy}\right)_{y=y_e}; \quad \left.\frac{dc}{d\xi}\right|_{y=0} = -\frac{1}{\varkappa_i}\left(c - \frac{dc}{dy}\right)_{y=0} \tag{8}$$

According to (3), the first condition of (8) yields

$$A_1'(\xi) + A_2'(\xi)e^{y_e} = \frac{1}{\varkappa_e}A_1(\xi), \tag{9}$$

while from the second condition

$$A_1'(\xi) + A_2'(\xi) = -\frac{1}{\varkappa_i}A_1(\xi). \tag{10}$$

From (9) and (10) we obtain

$$\frac{A_1'(\xi)}{A(\xi)} = -\varphi_p, \tag{11}$$

where

$$\varphi_p = \frac{1}{\varkappa_i}\,\frac{\exp y_e + (\varkappa_i/\varkappa_e)}{\exp y_e - 1}\,. \tag{12}$$

The solution (11) yields

$$A_1(\xi) = D_1 e^{-\varphi_p \xi}. \tag{13}$$

Analogously, we find

$$A_2(\xi) = D_1\left(\frac{1}{\varphi_p \varkappa_i} - 1\right)e^{-\varphi_p \xi} + D_2. \tag{14}$$

Substituting (13) and (14) into (3), we obtain

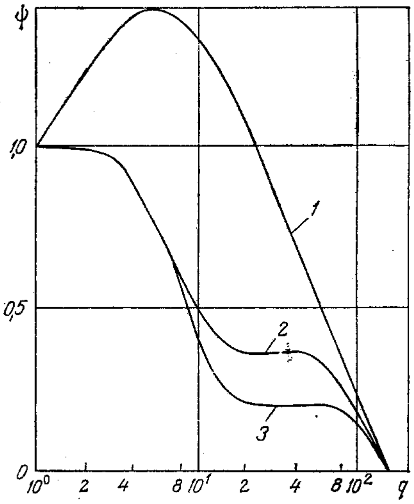

Fig. 3. Dependence of the comparative efficiency of the Frazier and central-feed column schemes on the degree of separation for $y_e = 5$: 1) $\varkappa_i/\varkappa_e = 1$; 2) 100; 3) 200.

$$c = D_1 e^{-\varphi_p \xi} + \left[D_1 \left(\frac{1}{\varphi_p \varkappa_i} - 1 \right) e^{-\varphi_p \xi} + D_2 \right] e^{y}. \tag{15}$$

For the ends of the column $y = y_e$ and $y = 0$, formula (15) yields

$$c_e = D_1 e^{-\varphi_p \xi} + \left[D_1 \left(\frac{1}{\varphi_p \varkappa_i} - 1 \right) e^{-\varphi_p \xi} + D_2 \right] e^{y_e}, \tag{16}$$

$$c_i = \frac{D_1}{\varphi_p \varkappa_i} e^{-\varphi_p \xi} + D_2. \tag{17}$$

The constants D_1 and D_2 in (16) and (17) are determined from the condition

$$c_e |_{\xi=0} = c_0; \quad c_i|_{\xi=0} = c_0, \tag{18}$$

from which

$$D_1 = c_0, \; D_2 = c_0 \left(1 - \frac{1}{\varphi_p \varkappa_i} \right). \tag{19}$$

Substituting the values obtained in (16) and (17), assuming $\xi = 1$, and replacing φ_p in (19) according to (12), we obtain the values of the stream concentrations emerging from the column:

$$c_{e\,\mathrm{out}} = c_0 \left[e^{-\varphi_p} + \left(1 + \frac{\varkappa_i}{\varkappa_e} \right) \frac{(1 - e^{-\varphi_p}) e^{y_e}}{e^{y_e} + (\varkappa_i/\varkappa_e)} \right], \tag{20}$$

$$c_{i\,\mathrm{out}} = c_0 \left[e^{-\varphi_p} + \left(1 + \frac{\varkappa_i}{\varkappa_e} \right) \frac{1 - e^{-\varphi_p}}{e^{y_e} + (\varkappa_i/\varkappa_e)} \right]. \tag{21}$$

From the condition of mass conservation in a column of the type under consideration, the equality

$$\varkappa_i c_{i\,\mathrm{out}} + \varkappa_e c_{e\,\mathrm{out}} = c_0 (\varkappa_i + \varkappa_e) \tag{22}$$

should hold. Substituting the values of the concentration from (20) and (21) shows that (22) is satisfied.

Taking account of (12), the degree of separation

$$q_p \equiv \frac{c_{e\,\mathrm{out}}}{c_{i\,\mathrm{out}}} = \frac{[1 + (\varkappa_i/\varkappa_e)] e^{y_e} - (\varkappa_i/\varkappa_e)(e^{y_e} - 1) e^{-\varphi_p}}{(e^{y_e} - 1) e^{-\varphi_p} + 1 + (\varkappa_i/\varkappa_e)} \tag{23}$$

depends on three parameters: $\varkappa_i$, $\varkappa_e$, y_e. The degrees of separation corresponding to the limit values of these parameters can be obtained from (23).

For large y_e

$$q_p = \left(1 + \frac{\varkappa_i}{\varkappa_e}\right) \exp\left(\frac{1}{\varkappa_i}\right) - \frac{\varkappa_i}{\varkappa_e}. \tag{24}$$

For large $\varkappa_i$

$$q_p = e^{y_e} - (e^{y_e} - 1) \exp\left[-\frac{1}{(e^{y_e} - 1)\varkappa_e}\right]. \tag{25}$$

As is seen from (7), for an unbounded growth in the length B of the column, the parameter $\varkappa_i$ tends to zero and $\varphi_p \rightarrow \infty$; hence from (23)

$$q_p = e^{y_e}; \tag{26}$$

i. e., the degree of separation becomes equal to that for a column operating in the recoveryless mode.

In the case of a countercurrent flow (Fig. 1b), the sign of $\varkappa_i$ in the boundary conditions (8) should be reversed, after which we obtain, by duplicating the same reasoning,

$$c = D_3 e^{\varphi_c} + \left[D_3 \left(\frac{1}{\varphi_c \varkappa_i} - 1\right) e^{\varphi_c \xi} + D_4\right] e^{y}. \tag{27}$$

The constants D_3 and D_4 are found from the conditions

$$c_e|_{\xi=0} = c_0, \quad c_i|_{\xi=1} = c_0 \tag{28}$$

and have the form

$$D_3 = c_0 \frac{e^{y_e} - (\varkappa_i/\varkappa_e)}{e^{y_e+\varphi_c} - (\varkappa_i/\varkappa_e)}, \quad D_4 = c_0 \frac{e^{\varphi_c} - (\varkappa_i/\varkappa_e)}{e^{y_e+\varphi_c} - (\varkappa_i/\varkappa_e)}.$$

Consequently, we obtain the following expressions for the concentration of each of the components at the column exit:

$$c_{e\,\mathrm{out}} = c_0 \left[e^{\varphi_c}\left(e^{y_e} - \frac{\varkappa_i}{\varkappa_e}\right) + \frac{\varkappa_i}{\varkappa_e} e^{y_e}(e^{\varphi_c} - 1)\right] \left(e^{y_e+\varphi_c} - \frac{\varkappa_i}{\varkappa_e}\right)^{-1}, \tag{29}$$

$$c_{i\,\mathrm{out}} = c_0 \left(e^{y_e} + e^{\varphi_c} - 1 - \frac{\varkappa_i}{\varkappa_e}\right) \left(e^{y_e+\varphi_c} - \frac{\varkappa_i}{\varkappa_e}\right)^{-1}, \tag{30}$$

in which

$$\varphi_c = \frac{1}{\varkappa_i} \frac{e^{y_e} - (\varkappa_i/\varkappa_e)}{e^{y_e} - 1}. \tag{31}$$

Formulas (29) and (30) also satisfy condition (22). We have for the degree of separation from (29) and (30)

$$q_c = \left[e^{\varphi_c}\left(e^{y_e} - \frac{\varkappa_i}{\varkappa_e}\right) + \frac{\varkappa_i}{\varkappa_e} e^{y_e}(e^{\varphi_c} - 1)\right] \left(e^{y_e} + e^{\varphi_c} - 1 - \frac{\varkappa_i}{\varkappa_e}\right)^{-1}. \tag{32}$$

An indeterminacy occurs in (32) for

$$\frac{\varkappa_i}{\varkappa_e} = e^{y_e} \tag{33}$$

which can be developed to yield

$$q_c = \frac{e^{2y_e} + \varkappa_i (e^{y_e} - 1)}{1 + \varkappa_i (e^{y_e} - 1)}. \tag{34}$$

If the parameter $\varkappa_i$ is sufficiently small, then

$$q_c = e^{2y_e}; \tag{35}$$

i. e., the degree of separation in this case is the square of the degree of separation for a column operating in the recoveryless mode.

As an analysis of (32) shows that (33) corresponds to the maximum value of the degree of separation for $\varkappa_i = 0.5$. For other values of $\varkappa_i$ the dependence of the degree of separation on the ratio $\varkappa_i/\varkappa_e$ also passes through a maximum, as is seen from Fig. 2. Unfortunately, it is impossible to express the dependence of the ratio $\varkappa_i/\varkappa_e$ corresponding to the maximum values of q_c, explicitly on $\exp y_e$ and $\varkappa_i$. It is seen from an examination of Fig. 2 that starting with some values of $\varkappa_i/\varkappa_e$, the degree of separation exceeds that in an ordinary thermodiffusion column operating without sampling, where this excess might be quite noticeable. Thus, for instance, for $\varkappa_i = 0.2$ the maximum value is $q_c \approx 1600$ while a column might yield $q = 148.4$ in the recoveryless mode, i. e., an 11-fold smaller quantity. There also results from Fig. 2 that the mentioned difference will grow with the diminution in $\varkappa_i$, i. e., for an unchanged value of the sampling with the increase in the column length B.

From (32) for large B and $\varkappa_i/\varkappa_e < e^{y_e}$

$$q_c = \left(1 + \frac{\varkappa_i}{\varkappa_e}\right) e^{y_e} - \frac{\varkappa_i}{\varkappa_e}, \tag{36}$$

where if the streams σ_i and σ_e are equal, then

$$q_c = 2e^{y_e} - 1, \tag{37}$$

i. e., a result close to that presented in [2] in which there is no 1 in the right side of (37).

When $\varkappa_i/\varkappa_e > e^{y_e}$ and B is large, from (32)

$$q_c = \frac{\varkappa_i}{\varkappa_e} e^{y_e} \left(1 - \frac{\varkappa_i}{\varkappa_e} - e^{y_e}\right)^{-1}. \tag{38}$$

The degree of separation calculated by means of (36) is always larger than that calculated from (38). Therefore, it is seen from (34)-(38) that a degree of separation considerably exceeding that in a column of equal height but operating in a mode without sampling can be achieved for an appropriate selection of the ratio between the streams.

Let us present two other limit cases: when the dimensionless height of the column y_e is large

$$q_c = \left(1 - \frac{\varkappa_i}{\varkappa_e}\right) \exp\left(\frac{1}{\varkappa_i}\right), \tag{39}$$

and when the parameter $\varkappa_i$ grows without limit for a constant quantity $\varkappa_e$, we obtain a formula identical to (25).

It was assumed in obtaining the results presented above that the longitudinal diffusion in the upper and lower channels of the column (Fig. 1a and b) is negligibly small.

A more complete description of the separation process in the column under consideration results, in place of (9) and (10), in a system of third-order differential equations to find the coefficients $A_1(\xi)$, $A_2(\xi)$ in which derivatives higher than the first may be neglected, as analysis shows, if the condition

$$\frac{f\rho D}{BH} \ll \varkappa_i \varkappa_e \frac{e^{y_e} - 1}{e^{y_e} + 1} \tag{40}$$

is conserved, where f is the channel cross-sectional area.

Therefore, all the formulas presented above are valid upon conservation of condition (40), which should be satisfied completely for not too small samples.

Now let us compare the Frazier countercurrent scheme with a column with central feed (Fig. 1c) in which the degree of separation, as can be shown, is

$$q_{\text{c.f.}} = \frac{\varkappa_e + 1}{\varkappa_i - 1} \cdot \frac{\varkappa_i - \exp\left[\frac{1}{2}(1 - \varkappa_i) y_e\right]}{\varkappa_e + \exp\left[-\frac{1}{2}(1 + \varkappa_e) y_e\right]} \tag{41}$$

It is expedient to use the quantity

$$\psi = \frac{Q^*_{\text{Fr}}}{Q^*_{\text{c.f.}}} \tag{42}$$

as the characteristic of the efficiency of both kinds of apparatus, where Q^*_{Fr}, $Q^*_{\text{c. f.}}$ are the specific heat expenditures per unit enriched product in the Frazier scheme and in the column with central feed, respectively.

The heat consumption in a plane thermodiffusion column is

$$Q = \frac{\lambda}{\delta} F\Delta T, \tag{43}$$

where the heat-transfer surface is F = BL and the height of the column can be expressed in terms of the coefficients of the transport equation H and K:

$$L = y_e \frac{K}{H}.$$

Then in place of (43) we have

$$Q = \frac{\lambda}{\delta} y_e \frac{KB}{H} \Delta T.$$

Dividing the left and right sides of this last expression by the sampling value σ_e, taking (7) into account, and replacing H and K by their values (see Notation), we obtain an expression for the specific heat expenditure in the form

$$Q^* = \frac{10}{7} \frac{y_e}{\varkappa_e} \frac{\lambda \bar{T}^2}{\alpha^2 \rho D \Delta T}.$$

Then according to (42) the efficiency characteristic for identical temperature modes is

$$\psi = \left(\frac{y_e}{\varkappa_e}\right)_{\mathrm{Fr}} \Big/ \left(\frac{y_e}{\varkappa_e}\right)_{\mathrm{c.f.}}. \tag{44}$$

Let us note that even in [3] attention had been turned to the fact that the ratio $y_e/\varkappa$ is a measure of the effectiveness of thermodiffusion apparatus with a constant cross section.

For $\psi < 1$ the Frazier scheme turns out to be energetically more favorable.

Formula (41) can be rewritten in another form:

$$q_{\mathrm{c.f.}} = \frac{[\varkappa_{\mathrm{c.f.}} + (\varkappa_i/\varkappa_e)]\left\{\varkappa_{\mathrm{c.f.}} - \exp\left[\frac{1}{2}(1-\varkappa_{\mathrm{c.f.}})y_e\right]\right\}}{(\varkappa_{\mathrm{c.f.}} - 1)\left\{\varkappa_{\mathrm{c.f.}} + (\varkappa_i/\varkappa_e)\exp\left[-\frac{1}{2}\left(1 + \frac{\varkappa_i}{\varkappa_e}\varkappa_{\mathrm{c.f.}}\right)y_e\right]\right\}}. \tag{45}$$

Assuming from (32) that both schemes are compared for equal degrees of separation,

$$\frac{1}{\varkappa_{\mathrm{c.f.}}} = \frac{e^{y_e} - 1}{e^{y_e} - (\varkappa_i/\varkappa_e)} \ln \frac{[e^{y_e} - (\varkappa_i/\varkappa_e) - 1]\, q_{\mathrm{Fr.}} + (\varkappa_i/\varkappa_e)\, e^{y_e}}{[1 + (\varkappa_i/\varkappa_e)]\, e^{y_e} - (\varkappa_i/\varkappa_e) - q_{\mathrm{c.f.}}}. \tag{46}$$

Determining the values of y_e and $\varkappa_i/\varkappa_e$ and being given $\varkappa_{\mathrm{c.f.}}$, we obtain a number of values of $q_{\mathrm{c.f.}}$ which yield, when substituted into (46), a quantity reciprocal to the dimensionless sampling in the scheme with transverse flows. Figure 3 illustrates the nature of the dependence of the comparative efficiencies of both schemes under consideration on the degree of separation. It is seen from this figure that the Frazier scheme is energetically more favorable for any degrees of separation for $\varkappa_i/\varkappa_e$, where the advantage of this scheme becomes ever more noticeable with the growth of the degree of separation. For $q > \exp y_e$ the Frazier column assures the requisite productivity, while a column with a central feed can yield only $q_{\mathrm{c.f.}} = \exp y_e$.

It should be mentioned that the advantage of the scheme with transverse streams should be apparent to an even greater degree when taking account of the dependence of the coefficients H and K in the transport equation on the sampling [4, 5].

The results presented above permit the conclusion that the Frazier scheme possesses a number of advantages justifying its practical application.

NOTATION

δ, working gap; B, column length in the x coordinate direction; L, column height, see Fig. 1; α, thermodiffusion constant; $\Delta T = T_1 - T_2$, temperature difference between the hot and cold surfaces; $\bar{T} = \frac{1}{2}(T_1 + T_2)$; $y_e = HL/K$; λ, coefficient of thermal conductivity; Q, heat consumption in the column; $\varkappa_e$, $\varkappa_i$, see (7); ξ, dimensionless coordinate, see (4); q, degree of separation; φ, see (12), (31); c, mass concentration,

$$H = \frac{\alpha \rho^2 g \beta \delta^3 (\Delta T)^2 B}{6! \eta \bar{T}}, \quad K = \frac{g^2 \rho^3 \beta^2 \delta^7 (\Delta T)^2 B}{9! \eta^2 D}$$

The remaining notation is standard. Indices: c, countercurrent; p, forward current; o, initial value; in, value at the entrance; out, value at the exit; e, positive end of the column; i, negative end of the column.

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FREE CONVECTION OF GAS MIXTURE ABOVE A FLAT HORIZONTAL PLATE IN CONSTANT-VELOCITY FLOW

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UDC 536.253

The problem of mixed convection for a mixture of viscous heat-conducting gases above a horizontal plate is solved by using the method of integral relations.

§ 1. In the present article the flow of a mixture of heat-conducting gases past a flat horizontal plate heated to a high temperature is considered under the assumption that everywhere in the flow region there exists the derivative $\partial/\partial y \gg \partial/\partial x$. If one carries out the same estimates as in the boundary-layer theory, and bearing in mind that the pressure is a resulting force, that is, it is of the order of the forces applied to the system, the following system of equations governing the proposed flow model is obtained:

$$\frac{\partial \rho v_x}{\partial x} + \frac{\partial \rho v_y}{\partial y} = 0; \tag{1.1}$$

$$\rho v_x \frac{\partial v_x}{\partial x} + \rho v_y \frac{\partial v_x}{\partial y} = -\frac{\partial P}{\partial x} + \frac{\partial}{\partial y}\mu\frac{\partial v_x}{\partial y}; \tag{1.2}$$

$$0 = -\frac{\partial P}{\partial y} + \rho F_y; \tag{1.3}$$

$$\rho v_x \frac{\partial h}{\partial x} + \rho v_y \frac{\partial h}{\partial y} = -\frac{\partial q_y}{\partial y} + v_x\frac{\partial P}{\partial x} + v_y\frac{\partial P}{\partial y} + \mu\left(\frac{\partial v_x}{\partial y}\right)^2; \tag{1.4}$$

$$\rho v_x \frac{\partial c_\alpha}{\partial x} + \rho v_y \frac{\partial c_\alpha}{\partial y} = -\frac{\partial}{\partial y} j_{\alpha y}, \quad \alpha = 1, 2, \ldots, N-1, \tag{1.5}$$

where

$$\sum_{\alpha=1}^{N} c_\alpha = 1, \quad h = \sum_{\alpha=1}^{N} c_\alpha h_\alpha, \quad \left(\frac{\partial h_\alpha}{\partial T}\right)_P = C_{P_\alpha}, \quad \sum_{\alpha=1}^{N} c_\alpha C_{P_\alpha} = \overline{C}_P.$$

If in the original gas mixture the concentration of one gas is much higher than that of the other gases, then by using the independent diffusion approximation and by bearing in mind that the term governing the effect of the pressure diffusion is small, one obtains for the diffusion-flow vector of the α-component

$$\bar{j}_\alpha = -\rho D_{1\alpha}\left(\nabla c_\alpha + \frac{k_{T_\alpha}}{T}\nabla T\right), \tag{1.6}$$

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