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A Thermal Diffusion Column with a Vertical Barrier

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Abstract

The intensification of the thermal diffusion process by installing a thin vertical barrier has been studied both theoretically and experimentally. The dependence of the separation on a barrier position has been obtained. It has been shown that in the modified column a higher production rate compared to the classical one may be obtained.

INTRODUCTION

The application of thermal diffusion (TD) as a separation method on a large scale is primarily hampered by a low product rate in a single column, large heat consumption, and high relaxation time. Hence much attention is focused on various methods of intensifying the TD proces. Many works deal with methods of obtaining the higher separation [a titled column (*1*), packed column (*2*)] but usually with a lower product rate. From a practical point of view, higher output is just as important as higher separation.

One of the methods of intensifying the thermal diffusion process which promises higher output from a column is the installation of thin permeable vertical barriers in the column operating space. The gaseous thermal diffusion column with vertical barrier has been studied experimentally by Treacy and Rich (*3*) and both theoretically and experimentally by Sasaki and co-workers (*4–6*). A different approach is presented by Bobrova and Rabinovich (*7*): they have used a barrier having a width comparable with the width of the column slit. These works have shown that the equilibrium separation factor obtained in columns with vertical barriers is larger than in classical columns. The dependence of separation on the barrier position has been studied theoretically only by Selecki et al. (*8*). This analysis leads to the conclusion that in both parts of the column slit an overlap of the flow caused by the difference of mean temperatures between both parts of the slit and the "normal" symmetrical thermogravitational flow in the respective parts of the slit occurs. Therefore in both parts of the column slit the "normal" thermogravitational flow is disturbed by flow between both parts of the slit (which may be considered as an additional flow). Hence, if these additional currents are retarded, the separation in the column will be further enhanced. The simplest idea of this flow inhibition is to place a permeable barrier not only in the operational space but also in both the top and bottom reservoirs (Fig. 1). Thus the inhibition (usually partial) of the additional convective flow takes place during the flow of the fluid through the parts of the barrier placed in the reservoirs.

In this paper the separation in the column with a thin permeable vertical barrier placed in the operating space and also in the column reservoirs has been studied.

THEORY

The heat transfer between the walls of the thermal diffusion column is determined by conduction (*9*). The temperature distribution in the fluid is linear (Fig. 2) and the temperature of the barrier walls may be determined by

$$T_2 = T_1 + (T_3 - T_1)\frac{a}{1 + p} \tag{1}$$

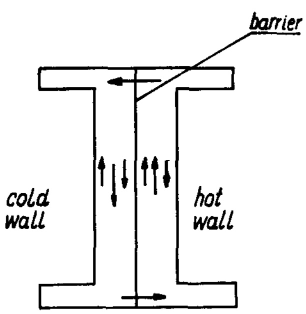

FIG. 1. Scheme of flows in a thermal diffusion column with barrier.

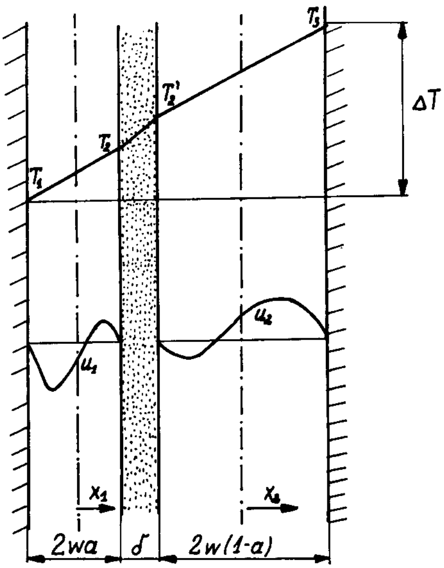

FIG. 2. Temperature distribution and velocity profile of flow in a thermal diffusion column with barrier.

$$T_2' = T_3 - (T_3 - T_1)\frac{1 - a}{1 + p} \tag{2}$$

where

$$p = \lambda_L \delta / \lambda_b 2w \tag{3}$$

The velocity profile (Fig. 2) of fluid flow in the operational slit of a TD column with a barrier may be described by (*8*)

$$u_1 = \frac{\beta \rho g \Delta T w^2 a^3}{12\mu}[\eta_1(1 - \eta_1^2) + \gamma A_1(1 - \eta_1^2)] \tag{4}$$

$$u_2 = \frac{\beta \rho g T w^2 (1 - a)^2}{12\mu}[\eta_2(1 - \eta_2^2) + \gamma A_2(1 - \eta_2^2)] \tag{5}$$

where

$$\eta_1 = \frac{x_1}{aw}, \qquad \eta_2 = \frac{x_2}{(1 - a)w} \tag{6}$$

$$A_1 = \frac{6(T_{m1} - \overline{T})}{\Delta T}, \qquad A_2 = \frac{6(T_{m2} - \overline{T})}{\Delta T} \tag{7}$$

$$T_{m1} = \frac{1}{2}(T_1 + T_2), \qquad T_{m2} = \frac{1}{2}(T'_2 + T_3) \tag{8}$$

and $\bar{T}$ is a mean temperature for calculations.

Functions A (defined by Eq. 7) are a measure of the convective flow between the parts of the column slit. The parameter γ is a measure of this flow inhibition:

$\gamma = 0$: the additional convective flow is fully inhibited
$\gamma = 1$: the additional convective flow is not retarded

For batch operation:

$$a\int_{-1}^{+1} \rho u_1 \, d\eta_1 + (1 - a)\int_{-1}^{+1} \rho u_2 \, d\eta_2 = 0 \tag{9}$$

and the Functions A may be determined in the form

$$A_1 = -(2p + 1)\frac{3(1 - a)^3}{a[a^3 + (1 - a)^3]} \tag{10}$$

$$A_2 = (2p + 1)\frac{3a^3}{(1 - a)[a^3 + (1 - a)^3]} \tag{11}$$

These equations show that the additional flows depend on the barrier position in the column slit and on the barrier characteristic parameters p and γ.

The net mass flow of a component in the column cross section equals

$$\tau = b\rho \int_{-w}^{+w} \left(cu - D\frac{\partial c}{\partial z} \right) dx \tag{12}$$

After integrating these expressions [by a generally known method (*10*)], the transport equation assumes the form

$$\tau = Hc(1 - c) - (K_c + K_d)\frac{dc}{dz} \tag{13}$$

where

$$H = H_0 h(a, \gamma) \tag{14}$$

$$K_c = K_{co} k(a, \gamma) \tag{15}$$

$$K_d = 2wb\rho D \tag{16}$$

and

$$h(a, \gamma) = a^5(1 - 5\gamma A_1) + (1 - a)^5(1 - 5\gamma A_2) - 10A_1\gamma a^4(1 - a) \tag{17}$$

$$k(a, \gamma) = a^9(1 - 7\gamma A_1 + 26\gamma^2 A_1^2) + (1 - a)^9(1 - 7\gamma A_2 + 26\gamma^2 A_2^2) + 70\gamma^2 A_1^2 a^8(1 - a) \tag{18}$$

$$H_o = \frac{\beta\rho^2 g b(2w)^3 \alpha(\Delta T)^2}{6!\mu T} \tag{19}$$

$$K_{co} = \frac{\rho^3\beta^2 g^2 b(2w)^7(\Delta T)^2}{9!\mu^2 D} \tag{20}$$

The equilibrium separation factor is defined as

$$q = \frac{c_T(1 - c_b)}{c_B(1 - c_T)} = \exp\left(\frac{HL}{K_c + K_d}\right) \tag{21}$$

For liquid separation and the slit width usually used ($2w > 0.2$ mm), the following condition holds (*11*):

$$K_c \gg K_d \tag{22}$$

and Eq. (21) may be written in the form

$$\ln q = \frac{h(a, \gamma)}{k(a, \gamma)} \ln q_o \tag{23}$$

where q_o is the equilibrium separation factor in a classical column of slit width equal to $2w$.

The calculated dependence given by Eq. (23) is presented in Fig. 3 (for $p = 0$). It is very interesting that the maximum of separation is obtained for an asymmetrical barrier position.

The problem of product draw off from a column with a barrier requires some discussion. Consider the classical column (without a barrier) giving the same equilibrium separation factor

$$q_o = \exp\left(\frac{H_o(2w_o, T_o)}{K_{co}(2w_o, T_o)} L\right) \tag{24}$$

as the column with the barrier

$$q = \exp\left(\frac{H(2w, T, a, \gamma)}{K_c(2w, T, a, \gamma)} L\right) \tag{25}$$

both columns being of equal height, breadth, and heat consumption. Then

$$\frac{2w_o}{2w} = \sqrt[4]{\frac{k(a, \gamma)}{h(a, \gamma)}} \tag{26}$$

$$\frac{\Delta T_o}{\Delta T} = \frac{2w_o}{2w} \tag{27}$$

If both columns give the same separation, then the normalized product draw off should be equal:

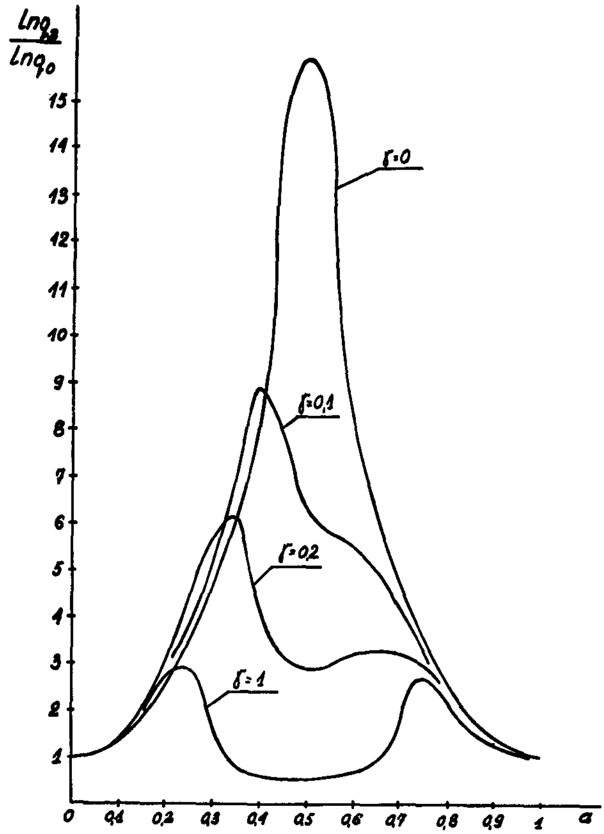

FIG. 3. The theoretical dependence of the equilibrium separation factor on the barrier position parameter a and the parameter γ.

$$\frac{P_o}{H_o(2w_o, T_o)} = \frac{P}{H(2w, T, a, \gamma)} \tag{28}$$

From the above relations the ratio of the product draw offs as a function of the parameters a and γ may be obtained:

$$\frac{P}{P_o} = \left[\frac{h(a, \gamma)}{k(a, \gamma)}\right]^{1.25} h(a, \gamma) \tag{29}$$

Figure 4 presents the calculated dependence (29). This relation shows that for the optimum barrier position, the draw offs in the column with a barrier are 2 to 2.5 times higher than in the classical column.

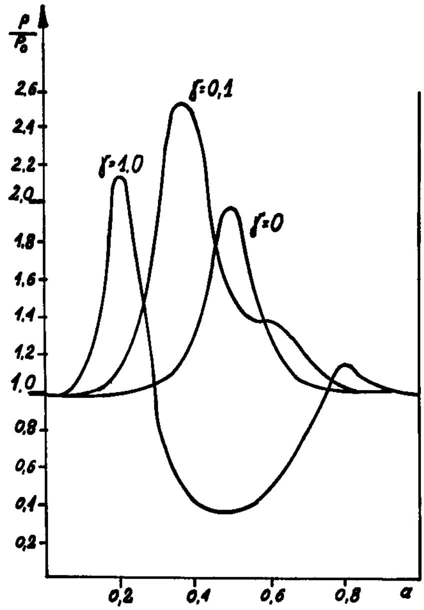

FIG. 4. The theoretical dependence of production rate on parameters a and γ.

EXPERIMENTS

Experiments were performed by using a flat plate thermal diffusion column of 0.13 m height and 0.15 m breadth. The distance between the walls was 1.7 mm. A few layers of thin sheet gaskets with spacers were placed between the walls. Cotton fabric of 0.2 mm thickness was used as a barrier. The barrier position in the operational space was changed by placing the fabric between the appropriate gasket layers. The hot wall had a temperature of 363°K; the cold wall, 283°K. A zinc sulfate water solution of 9.4% mass concentration was used as the fluid to be separated in the column. A single experiment lasted for 10 hr. It was experimentally verified that this time is sufficient to achieve equilibrium.

The dependence of the equilibrium separation factor on the barrier position as obtained experimentally is presented in Fig. 5. The dotted line shows the theoretical dependency calculated for $\gamma = 0.4$. The results obtained show qualitative agreement with theoretical predictions. An exact quantitative comparison of experimental results with theoretical prediction was impossible because the degree of the additional convective flow inhibition (parameter γ) was undefined. However, the optimum barrier position is in good agreement with the theoretical calculated value.

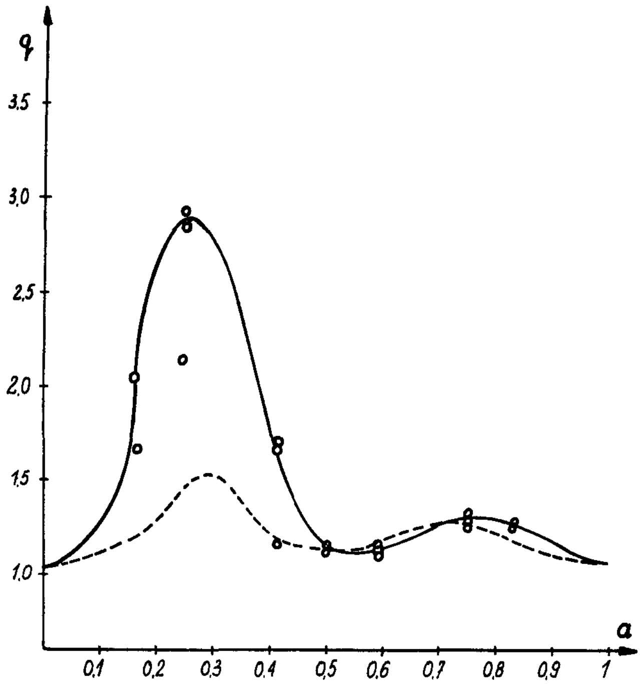

FIG. 5. The dependency of the equilibrium separation factor on the barrier position.

The fact that the smallest separation values obtained in the column with a barrier are higher than those calculated for the column without a barrier must be pointed out. This shows that the proposed installation of the barrier in the column reservoirs results in partial inhibition of additional convective flow. The values of the equilibrium separation factor are much higher (in particular when the barrier was placed near the cold wall) than the theoretical calculated values. The reasons for this are not clear. It may be that additional factors, not taken into consideration in the theoretical description, may cause an increase in separation. For example, the installation of a barrier may result in partial inhibition of the total convective flow in the column.

The barrier-divided operational space of the column is in two parts. Thus the separation process with product draw off may be conducted using different methods of feeding the column and drawing off the products from the top and bottom reservoirs. For example, the feed may be flowed into the part of the column between the barrier and the hot wall (so-called "hot part of the slit"), and both top and bottom products may be drawn off from the part of the column between the barrier and the cold wall (so-called "cold part of the slit"). The feed and product drawn off methods used in experiments are presented in Table 1. The flow rates were selected so that the rate of product draw off from the top reservoir was equal to the rate of the bottom product draw off. The products flowed from the opposite side of the column to the feed point.

Figure 6 shows the experimental results. For connections of feed and draw offs 3 and 4, the separations were considerably smaller than in the other experiments and are not presented in Fig. 6. For comparison, separation in a column without a barrier and with product draw off was investigated. The distance between the column walls was 0.7 mm in this case.

The dependencies presented show that in a column with a barrier, higher separation factors are obtained for the same draw offs compared to a classical column.

Experimental results show that the separation factor obtained in columns with a barrier depends on the method of feeding the column and the top and bottom product draw off. This is due to the different division of flow between the parts of the column slit separated by the barrier, depending on the feeding and product draw off method.

CONCLUSION

Theoretical and experimental studies show that the modification of the thermal diffusion column by installing a thin barrier permeable to mass transfer is an effective method of intensifying this process. A modified column gives higher separation as compared with a classical column. The existence of an optimum position of the barrier in the slit has been shown. The experimental results show that in a modified column a higher product draw off as compared with a classical column may be obtained.

TABLE 1

Methods of Feeding the Column and Drawing Off the Products

No.	Feed to	Top product from	Bottom product from
1	Hot part of slit	Cold part of slit	Cold part of slit
2	Hot part of slit	Hot part of slit	Hot part of slit
3	Both parts of slit	Both parts of slit	Both parts of slit
4	Cold part of slit	Cold part of slit	Cold part of slit

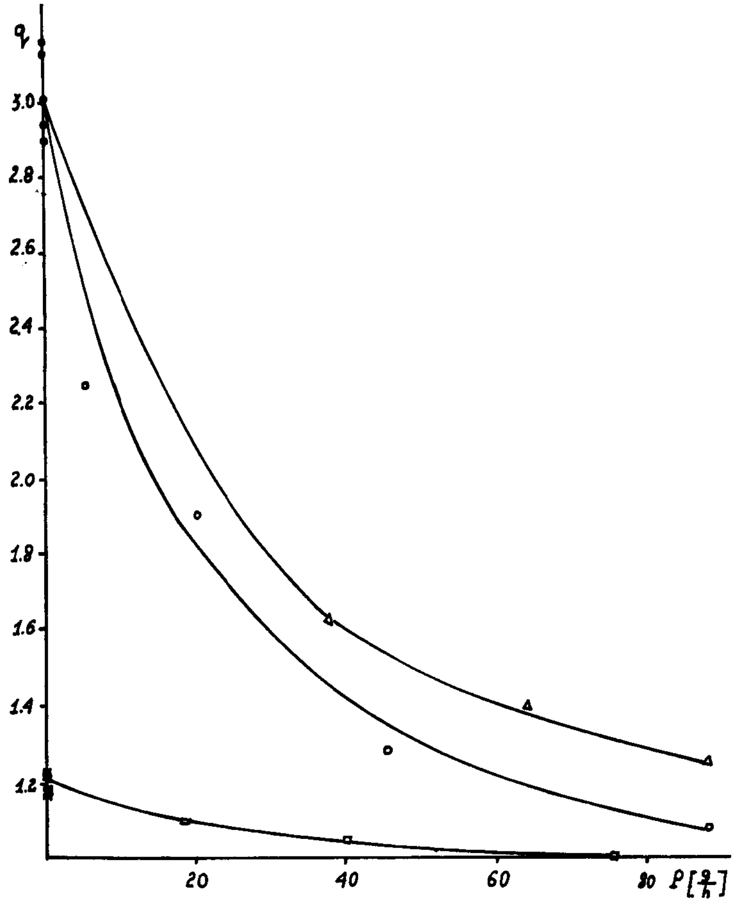

FIG. 6. The dependence of separation on production rate: (○) Connection 1, (△) Connection 2, (□) column without barrier, with $a = 0.25$.

SYMBOTS

a	design parameter
A_1, A_2	parameters defined by Eq. (7)
b	breadth of the column
c	concentration
D	diffusion coefficient
g	gravitational acceleration
h	function defined by Eq. (17)
H	coefficient in the transport equation
k	function defined by Eq. (18)

K_c, K_d	coefficients in the transport equation
L	height of the column
p	parameter defined by Eq. (3)
P	rate of draw off
q	separation factor
T	temperature
$\bar{T}$	reference temperature
u	linear velocity of the fluid
w	half width of the operating space
x, z	coordinates

Greek Letters

α	thermal diffusion constant
β	temperature coefficient of the density
δ	width of a barrier
η	dimensionless coordinate
λ	thermal conductivity
μ	viscosity
ρ	density
τ	net upward rate transport of light component
γ	additional convective flow inhibition coefficient

Subscripts

B	bottom of the column
b	barrier
l	liquid
m	mean
T	top of the column
o	classical TD column

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