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A theoretical study of the improvement in performance of double-pass mass exchangers with external refluxes separated by an idealized permeable barrier

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Abstract

A design of inserting in parallel an impermeable sheet or a permeable barrier to divide an open duct into two channels for double-pass operations with uniform wall concentration and external refluxes at the ends, resulting in substantially improving the mass transfer, has been proposed and investigated theoretically. The results are represented graphically and compared with those in an open duct (without an impermeable sheet or a permeable barrier inserted and, thus, with single-pass operations). Considerable improvement in mass transfer is obtainable by employing such a double-pass device with external refluxes, instead of using an open conduit with single-pass operations. The effect of impermeable-sheet or permeable-barrier location on the enhancement of mass-transfer efficiency as well as on the increment of power consumption, has been also discussed.

Keywords: Mass exchangers; Double-pass operation; External refluxes

1. Introduction

The Graetz problems concerning heat and mass transfer at steady state in a bounded conduit have been studied with ignoring axial conduction or diffusion [2,5,22,23]. Dealing with multiphase or multi-stream problems coupling through conjugated conduction–convection conditions at the boundaries is called conjugated Graetz problems [3,6,8,9,12,17–21,26,27].

Recycle effect has a significant influence on heat and mass transfer and, hence, plays a remarkable role in the design and operation of the equipment, such as loop reactors [14,15], air-lift reactors [7,24] and draft-tube bubble columns [11,16]. The design with the use of internal or external refluxes in the multi-pass mass exchangers is broadly used in chemical and process industrial, such as catalytic reactors [1], filters [25], gas scrubbers [4] and gas absorbers [13]. Moreover, the position of a permeable barrier in mass exchangers or an impermeable sheet in heat exchangers is the important factor to be considered to design heat and mass transfer processes in improving the performance of multi-pass devices.

It is known that with constant transfer area and flow rate of fluid, increasing the fluid velocity in the flow channel will enhance the transfer coefficients, resulting in improved the performance of heat or mass exchanger. A new device with the use of recycle-effect and multi-pass concept for increasing the fluid velocity but with the transfer area as well as the aspect ratio kept unchanged, is designed by inserting in parallel a permeable barrier or an impermeable sheet in the conduit to divide it into two subchannels, subchannel ‘a’ and subchannel ‘b’, thereby leading to improved performance. It is the purpose of present study to investigate the improvement in mass-transfer efficiency of such double-pass devices with a permeable barrier and an impermeable sheet inserted and to discuss the influence of the positions of a permeable barrier and an impermeable sheet on the device performance.

2. The governing equations for concentration distributions

Consider the mass transfer in two channels, subchannel ‘a’ and subchannel ‘b’, with thickness ΔW and $(1-\Delta)W$, respectively, which is designed by inserting a permeable barrier (or impermeable sheet) with negligible thickness δ ($\ll W$), into a parallel conduit of thickness W, length L, and width B ($\gg W$), as shown in Fig. 1. The membrane may be

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Nomenclature

B	conduit width (m)
C	concentration in the stream (kg mol/m^3)
D	ordinary diffusion coefficient in binary mixtures (m^2/s)
$F_{a,m}$, $F_{b,m}$	eigenfunction associated with eigenvalue $\lambda_{a,m}$ and $\lambda_{b,m}$, respectively
$F'_{a,m}$, $F'_{b,m}$	derivative of $F_{a,m}$, $F_{b,m}$ with respect to η_a and η_b, respectively
G_m	function defined during the use of orthogonal expansion method
Gz_m	mass Graetz number, VW/DBL
I_m, $I_{m,t}$	improvement of mass-transfer efficiencies, defined by Eqs. (30) and (31)
I_p	increment of power consumption, defined by Eq. (32)
k_m	average convection mass transfer coefficient (m/s)
ℓw_f	friction loss in conduit (kJ/kg)
L	conduit length (m)
R	reflux ratio, reverse volume flow rate divided by input volume flow rate
$S_{a,m}$, $S_{b,m}$	expansion coefficient associated with eigenvalue $\lambda_{a,m}$ and $\lambda_{b,m}$, respectively
Sh	Sherwood number, $k_m W/D$
v	velocity distribution of fluid (m/s)
$\bar{v}$	average velocity of fluid (m/s)
V	input volume flow rate of conduit (m^3/s)
W	distance between two parallel plates (m)
x	transversal coordinate (m)
z	longitudinal coordinate (m)

Greek letters

δ	thickness of the permeable barrier (m)
Δ	ratio of channel thickness, W_a/W
ε	ε is equal to the ratio of the pore area to membrane area multiplied by the number of pores
η	transversal coordinate, x/W
$\lambda_{a,m}$, $\lambda_{b,m}$	eigenvalues
θ	dimensionless temperature $(C-C_i)/(C_s-C_i)$
ξ	longitudinal coordinate, z/L
ψ	dimensionless temperature $(C-C_s)/(C_i-C_s)$

Superscript

t	in a double-pass device with inserting an insulation sheet

Subscripts

a	in forward flow channel
b	in backward flow channel
F	at the outlet of a double-pass device
i	at the inlet
s	at the wall surface
t	in a double-pass device with inserting an insulation sheet
0	in a single-pass device without recycle

also permeable to the non-diffusing species if there exists pressure difference on the both sides of membrane. However, we only consider the case of uniform pressure. There is no concentration profile at the mid-point in the presence of an impermeable sheet while a linear concentration gradient was achieved inside the barrier with the device of inserting an idealized permeable barrier. The fluid first flow through subchannel ‘a’ and then turn back to flow through subchannel ‘b’ with premixing the fluid exiting from this subchannel of flow rate RV and outlet concentration C_F, which is regulated by means of a conventional pump situated at the end of subchannel ‘b’.

After the following assumptions are made in present analysis: constant physical properties and wall concentration, negligible axial diffusion as well as entrance length and end effects, purely fully-developed laminar flow in each channel, mass transfer by diffusion only through the device with permeable barrier inserted. The velocity distributions in dimensionless form may be written as

$$v_a(\eta_a) = \bar{v}_a(6\eta_a - 6\eta_a^2), \quad 0 \le \eta_a \le 1 \tag{1}$$

$$v_b(\eta_b) = \bar{v}_b(6\eta_b - 6\eta_b^2), \quad 0 \le \eta_b \le 1 \tag{2}$$

where

$$\bar{v}_a = \frac{(R+1)V}{W_a B}, \quad \bar{v}_b = -\frac{V}{W_b B}, \quad \eta_a = \frac{x_a}{W_a},$$
$$\eta_b = \frac{x_b}{W_b}, \quad \xi = \frac{z}{L}, \quad Gz_m = \frac{V(W_a + W_b)}{DBL} = \frac{VW}{DBL},$$
$$W_a = \Delta W, \quad W_b = (1-\Delta)W \tag{3}$$

2.1. Double-pass operations with inserting an impermeable sheet

For the double-pass device, the permeable barrier in Fig. 1 is changed by inserting an impermeable sheet. The equations of mass transfer in dimensionless form may be obtained as

$$\frac{\partial^2 \psi_a(\eta_a,\xi)}{\partial \eta_a^2} = \left(\frac{W_a^2 v_a}{LD}\right)\frac{\partial \psi_a(\eta_a,\xi)}{\partial \xi} \tag{4}$$

$$\frac{\partial^2 \psi_b(\eta_b,\xi)}{\partial \eta_b^2} = \left(\frac{W_b^2 v_b}{LD}\right)\frac{\partial \psi_b(\eta_b,\xi)}{\partial \xi} \tag{5}$$

where

$$\psi_a = \frac{C_a - C_s}{C_i - C_s}, \quad \psi_b = \frac{C_b - C_s}{C_i - C_s},$$
$$\theta_a = 1 - \psi_a, \quad \theta_a = 1 - \psi_a \tag{6}$$

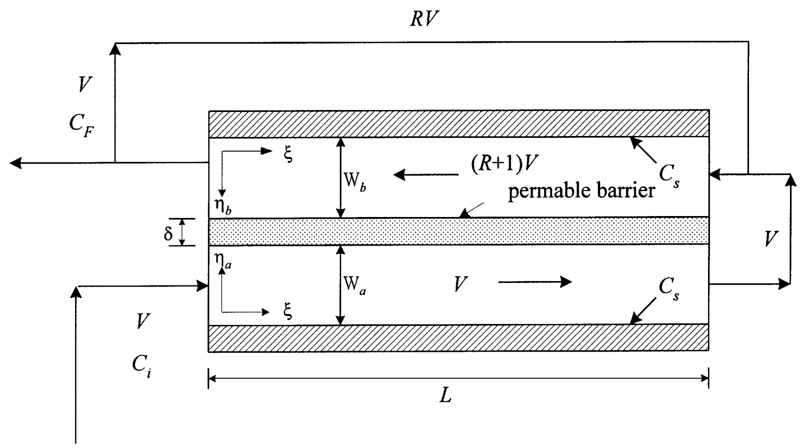

Fig. 1. Double-pass parallel-plate mass exchangers with external refluxes at both ends.

The boundary conditions for solving Eqs. (4) and (5) are

$$\psi_a(0,\xi)=0 \tag{7}$$

$$\psi_b(0,\xi)=0 \tag{8}$$

$$\left.\frac{\partial\psi_a}{\partial\eta_a}\right|_{\eta_a=1}=0 \tag{9}$$

$$\left.\frac{\partial\psi_b}{\partial\eta_b}\right|_{\eta_b=1}=0 \tag{10}$$

2.2. Double-pass operations with inserting a permeable barrier

Similarly, for the double-pass device, a permeable barrier inserted as shown in Fig. 1. The equations of mass transfer in dimensionless form may also be written as

$$\frac{\partial^2\psi_{a,t}(\eta_a,\xi)}{\partial\eta_a^2}=\left(\frac{W_a^2v_a}{LD}\right)\frac{\partial\psi_{a,t}(\eta_a,\xi)}{\partial\xi} \tag{11}$$

$$\frac{\partial^2\psi_{b,t}(\eta_b,\xi)}{\partial\eta_b^2}=\left(\frac{W_b^2v_b}{LD}\right)\frac{\partial\psi_{b,t}(\eta_b,\xi)}{\partial\xi} \tag{12}$$

where

$$\psi_{a,t}=\frac{C_{a,t}-C_s}{C_i-C_s},\quad \psi_{b,t}=\frac{C_{b,t}-C_s}{C_i-C_s},\quad \theta_{a,t}=1-\psi_{a,t},\quad \theta_{b,t}=1-\psi_{b,t} \tag{13}$$

The boundary conditions for solving Eqs. (11) and (12) are

$$\psi_{a,t}(0,\xi)=0 \tag{14}$$

$$\psi_{b,t}(0,\xi)=0 \tag{15}$$

$$-\frac{\partial\psi_{a,t}(1,\xi)}{\partial\eta_a}=\frac{W_a}{W_b}\frac{\partial\psi_{b,t}(1,\xi)}{\partial\eta_b} \tag{16}$$

$$\frac{\partial\psi_{a,t}(1,\xi)}{\partial\eta_a}=\frac{W_a\varepsilon}{\delta}[\psi_{b,t}(1,\xi)-\psi_{a,t}(1,\xi)] \tag{17}$$

where Eqs. (16) and (17) express that some amount of solute in channel 'b' is transferred by diffusion through the permeable barrier and the amount of mass flux are equal at the mutual boundary, respectively, while ε is equal to the ratio of the pore area to membrane area multiplied by the number of pores.

2.3. Single-pass operations without external refluxes

For the single-pass device of same size without external refluxes, $R=0$, and the permeable barrier in Fig. 1 is removed and, thus, $\Delta=1$, $W_a=W$ and $\eta_a=\eta_0$. The velocity distribution and equation of mass transfer in dimensionless form may then be expressed as

$$\frac{\partial^2\psi_0(\eta_0,\xi)}{\partial\eta_0^2}=\left(\frac{W^2v_0(\eta_0)}{LD}\right)\frac{\partial\psi_0(\eta_0,\xi)}{\partial\xi} \tag{18}$$

$$v_0(\eta_0)=\frac{V}{WB}(6\eta_0-6\eta_0^2),\quad 0\le\eta_0\le 1 \tag{19}$$

where

$$\eta_0=\frac{x}{W},\quad \xi=\frac{z}{L},\quad \psi_0=\frac{C_0-C_s}{C_i-C_s},\quad \theta_0=1-\psi_0 \tag{20}$$

The boundary conditions for solving Eq. (18) are

$$\psi_0(0,\xi)=0 \tag{21}$$

$$\psi_0(1,\xi)=0 \tag{22}$$

2.4. Calculation procedures

By following the similar mathematical treatment performed in our previous works [10], except the type of reflux, the dimensionless outlet concentrations for double-pass devices by inserting a permeable barrier ($\theta_{F,t}$) or an impermeable sheet (θ_F) as well as for single-pass device ($\theta_{0,F}$) were also obtained in terms of the mass Graetz number (Gz_m), eigenvalues ($\lambda_{m,t}$, $\lambda_{a,m}$, $\lambda_{b,m}$ and $\lambda_{0,m}$) expansion coefficients ($S^t_{a,m}$, $S^t_{b,m}$, $S_{a,m}$, $S_{b,m}$ and $\lambda_{0,m}$), location of

Table 1
The improvement of the mass-transfer efficiency (I_m, %) with reflux ratio and sheet position as parameters of double-pass operations by inserting an impermeable sheet

Gz_m	$R = 0.1$			$R = 0.5$			$R = 1.0$		
	$\Delta = 0.25$	$\Delta = 0.5$	$\Delta = 0.75$	$\Delta = 0.25$	$\Delta = 0.5$	$\Delta = 0.75$	$\Delta = 0.25$	$\Delta = 0.5$	$\Delta = 0.75$
1	0.03	0.02	0.02	0.04	0.03	0.03	0.05	0.04	0.04
10	30.06	15.34	27.06	36.7	16.49	28.31	37.70	18.21	29.79
100	63.21	30.33	63.01	70.10	30.57	67.10	71.68	30.93	69.20
1000	75.11	32.55	75.01	75.79	32.57	75.70	76.52	32.61	76.23

Table 2
The improvement of the mass-transfer efficiency ($I_{m,\mathrm{t}}$, %) with reflux ratio and barrier position as parameters of double-pass operations by inserting a permeable barrier ($\varepsilon(W/\delta) = 5$)

Gz_m	$R = 0.1$			$R = 0.5$			$R = 1.0$		
	$\Delta = 0.25$	$\Delta = 0.5$	$\Delta = 0.75$	$\Delta = 0.25$	$\Delta = 0.5$	$\Delta = 0.75$	$\Delta = 0.25$	$\Delta = 0.5$	$\Delta = 0.75$
1	−19.39	−22.80	−17.54	−12.12	−20.35	−16.40	−2.96	−17.69	−15.11
10	44.46	25.30	31.67	60.39	32.02	35.30	82.61	40.75	40.95
100	390.29	199.27	217.82	556.38	240.63	241.44	985.60	291.97	270.49
1000	631.39	271.29	296.83	1050.36	337.09	334.62	3424.22	425.06	383.14

permeable barrier or impermeable sheet (Δ) and eigenfunctions ($F^{\mathrm{t}}_{\mathrm{a},m}(\eta_{\mathrm{a}})$, $F^{\mathrm{t}}_{\mathrm{b},m}(\eta_{\mathrm{b}})$, $F_{\mathrm{a},m}$ (η_{a}), $F_{\mathrm{b},m}$ (η_{b}) and $F_{0,m}$ (η_0)). The results are

$$\theta_{\mathrm{F}} = 1 - \psi_{\mathrm{F}} = \frac{1}{Gz_m}\left[\sum_{m=0}^{\infty}\frac{(1-\mathrm{e}^{-\lambda_{\mathrm{a},m}})}{\lambda_{\mathrm{a},m}\Delta}S_{\mathrm{a},m}F'_{\mathrm{a},m}(0) + \sum_{m=0}^{\infty}\frac{(1-\mathrm{e}^{-\lambda_{\mathrm{b},m}})}{\lambda_{\mathrm{b},m}(1-\Delta)}S_{\mathrm{b},m}F'_{\mathrm{b},m}(0)\right] \tag{23}$$

$$\theta_{\mathrm{F,t}} = 1 - \psi_{\mathrm{F,t}} = \frac{1}{Gz_m}\left[\sum_{m=0}^{\infty}\frac{(1-\mathrm{e}^{-\lambda_{m,\mathrm{t}}})}{\lambda_{m,\mathrm{t}}\Delta}S^{\mathrm{t}}_{\mathrm{a},m}(F^{\mathrm{t}}_{\mathrm{a},m})'(0) + \sum_{m=0}^{\infty}\frac{(1-\mathrm{e}^{-\lambda_{m,\mathrm{t}}})}{\lambda_{m,\mathrm{t}}(1-\Delta)}S^{\mathrm{t}}_{\mathrm{b},m}(F^{\mathrm{t}}_{\mathrm{b},m})'(0)\right] \tag{24}$$

$$\theta_{0,\mathrm{F}} = 1 - \psi_{0,\mathrm{F}} = \frac{1}{Gz_m}\sum_{m=0}^{\infty}\left[\frac{(1-\mathrm{e}^{-\lambda_{0,m}})}{\lambda_{0,m}}S_{0,m}F'_{0,m}(0) - \frac{(1-\mathrm{e}^{-\lambda_{0,m}})}{\lambda_{0,m}}S_{0,m}F'_{0,m}(1)\right] \tag{25}$$

where the eigenvalues ($\lambda_{m,\mathrm{t}}$) for the device with a permeable barrier inserted were calculated from the following equations:

$$\frac{S_{\mathrm{a},m}}{S_{\mathrm{b},m}} = \frac{\Delta\varepsilon(W/\delta)F_{\mathrm{b},m}(1)}{\Delta\varepsilon(W/\delta)F_{\mathrm{a},m}(1) + F'_{\mathrm{a},m}(1)} = -\frac{\Delta}{(1-\Delta)}\frac{F'_{\mathrm{b},m}(1)}{F'_{\mathrm{a},m}(1)} \tag{26}$$

3. Improvement of mass-transfer efficiency

By following the same definition in the previous work [10], the Sherwood number for double-pass devices by inserting an impermeable sheet and by inserting a permeable barrier may be calculated as follows:

$$Sh = \frac{k_m W}{D} = \frac{VW}{2DBL}(1-\psi_{\mathrm{F}}) = 0.5Gz_m(1-\psi_{\mathrm{F}}) = 0.5Gz_m\theta_{\mathrm{F}} \tag{27}$$

for inserting an impermeable sheet, and

$$Sh_{\mathrm{t}} = \frac{k_{m,\mathrm{t}}W}{D} = \frac{VW}{2DBL}(1-\psi_{\mathrm{F,t}}) = 0.5G_{Z,m}(1-\psi_{\mathrm{F,t}}) = 0.5Gz_m\theta_{\mathrm{F,t}} \tag{28}$$

for inserting a permeable barrier. Similarly, for a single-pass device without recycle

$$Sh_0 = \frac{k_{0,m}W}{D} = \frac{VW}{2DBL}(1-\psi_{0,\mathrm{F}}) = 0.5Gz_m\theta_{0,\mathrm{F}} \tag{29}$$

The improvement of mass-transfer efficiencies, I_m and $I_{m,\mathrm{t}}$, for double-pass devices by inserting an impermeable sheet and by inserting a permeable barrier, respectively, are best illustrated by calculating the percentage increase in mass-transfer rate, based on the mass transfer of a single-pass device of same mass Graetz number without recycle as

$$I_m = \frac{Sh - Sh_0}{Sh_0} = \frac{\psi_{0,\mathrm{F}} - \psi_{\mathrm{F}}}{1-\psi_{0,\mathrm{F}}} = \frac{\theta_{\mathrm{F}} - \theta_{0,\mathrm{F}}}{\theta_{0,\mathrm{F}}} \tag{30}$$

and

$$I_{m,\mathrm{t}} = \frac{Sh_{\mathrm{t}} - Sh_0}{Sh_0} = \frac{\psi_{0,\mathrm{F}} - \psi_{\mathrm{F,t}}}{1-\psi_{0,\mathrm{F}}} = \frac{\theta_{\mathrm{F,t}} - \theta_{0,\mathrm{F}}}{\theta_{0,\mathrm{F}}} \tag{31}$$

The results are shown in Tables 1 and 2.

Table 3
The results of case 1

L (cm)	V (cm^3)	Gz_m	Sh_0	$I_{m,t}$ (%)		
				$R = 0.1$	$R = 0.5$	$R = 1.0$
30	0.5	250	3.61	228.53	281.75	332.67
	2.0	1000	3.65	271.29	337.09	425.06
60	0.5	125	3.53	209.72	250.12	300.95
	2.0	500	3.64	260.71	326.64	411.21

Table 4
The results of case 2

L (cm)	V (cm^3)	Gz_m	Sh_0	$I_{m,t}$ (%)		
				$R = 0.1$	$R = 0.5$	$R = 1.0$
10	50	10	2.62	25.30	32.02	40.75
	500	100	3.53	199.27	240.63	291.97
20	50	5	1.94	−5.15	1.03	3.67
	500	50	3.41	143.11	153.91	164.83

4. Numerical examples

The improvement in mass-transfer efficiency by arranging the recycle effect will be illustrated by the following two case studies. Consider the mass transfer for a fluid flowing through a parallel conduit with recycle. The working dimensions are: $B = 0.2$ m, $W = 0.02$ m, $\Delta = 0.5$, $\varepsilon = 0.125$ and $\delta = 5 \times 10^{-4}$ m.

Case 1: At 20 °C water is flowing through a parallel conduit made of benzoic acid. The numerical values are

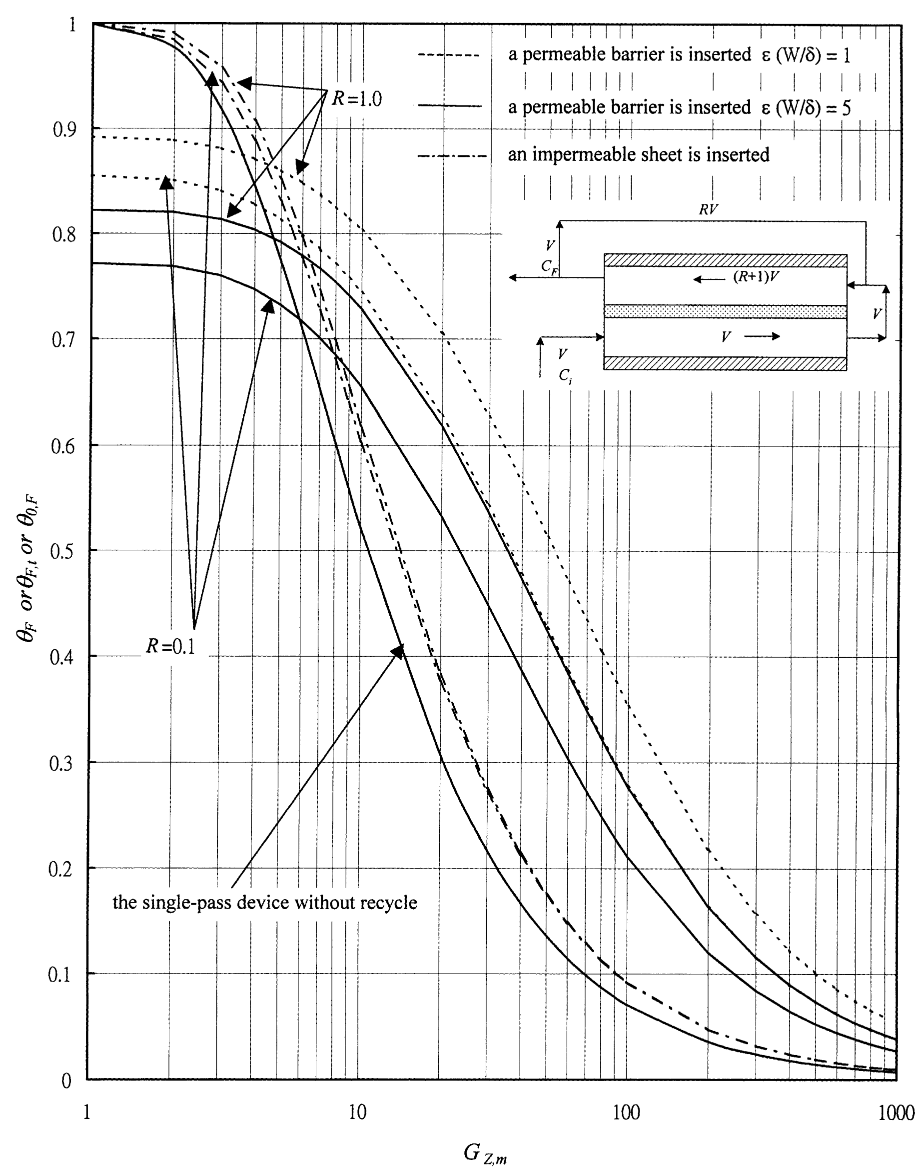

Fig. 2. Dimensionless average outlet concentration of three devices vs. Gz_m with reflux ratio as a parameter ($\Delta = 0.5$).

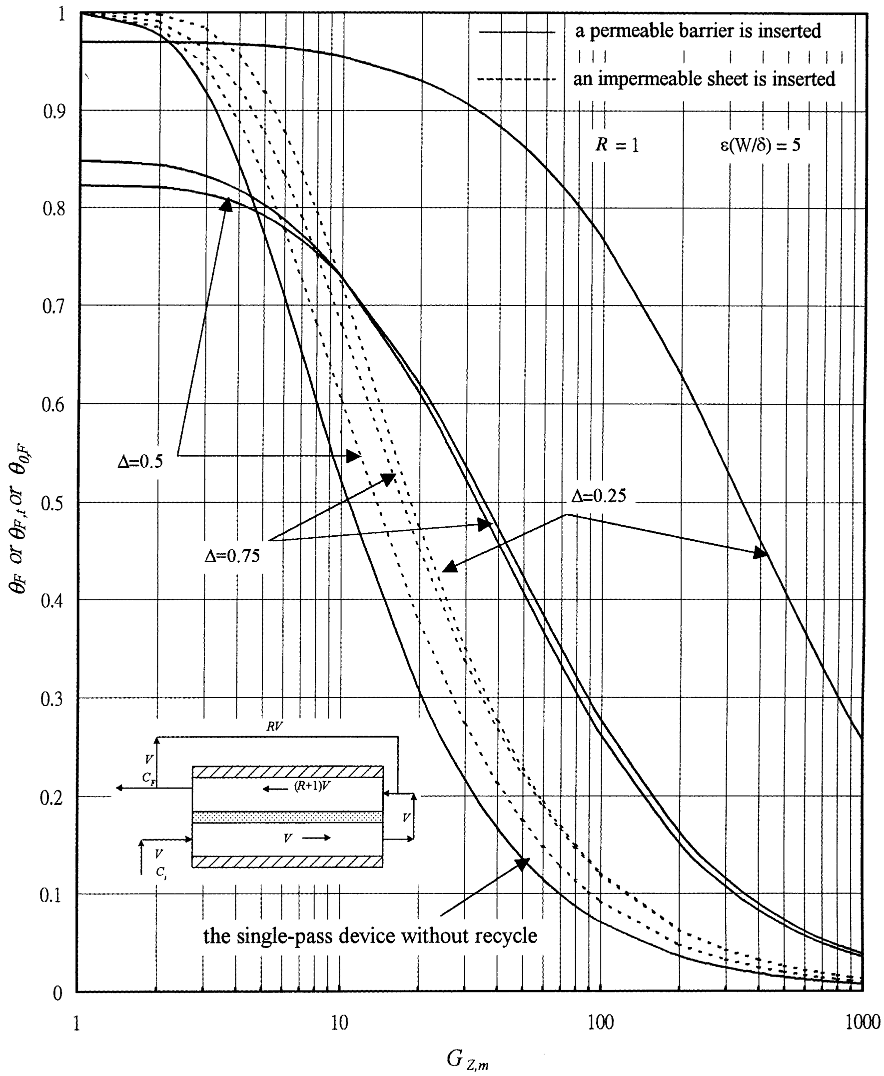

Fig. 3. Dimensionless average outlet concentration of both double-pass devices vs. Gz_m with Δ as a parameter ($R = 1$).

assigned as

$$C_i = 0, \quad C_s\,(\text{kmol/m}^3) = 1.97 \times 10^{-6}, \quad D\,(\text{m}^2/\text{s}) = 6.67 \times 10^{-10}$$

Case 2: Dry air at 1 atm and 10 °C is flowing through the parallel conduit made of naphthalene. The numerical values are assigned as

$$C_i = 0, \quad C_s\,(\text{kmol/m}^3) = 1.19 \times 10^{-6}, \quad D\,(\text{m}^2/\text{s}) = 5 \times 10^{-6}$$

From these values, the improvements in transfer efficiency in a parallel-plate mass exchanger operated with recycle arrangement under various flow rates of fluid and reflux ratios, were calculated by the appropriate equations and the results are presented in Tables 3 and 4.

5. Results and discussion

The calculation methods and procedure are similar to those in the previous work [10], and the results, thus, obtained will be discussed. The effects of the reflux ratio R and mass Graetz number Gz_m, as well as the impermeable-sheet (or permeable-barrier) position Δ on the average Sherwood number and dimensionless outlet concentrations, Sh, Sh_t, θ_F, $\theta_{F,t}$ and $\theta_{0,F}$ are in the same tendency as those in the previous work [10]. All Sh, Sh_t, θ_F, $\theta_{F,t}$ and $\theta_{0,F}$ increase with R but decrease as Gz_m increases.

Fig. 2 shows the relation of the useful graph of dimensionless outlet concentration ($\theta_{F,t}$ and θ_F) versus Gz_m with the reflux ratio R and $\varepsilon(W/\delta)$ as parameters for $\Delta = 0.5$ while Fig. 3 with the ratio of channel thickness Δ as a parameter. The results in Figs. 2 and 3 as well as in Tables 1 and 2 show that the dimensionless average outlet concentra-

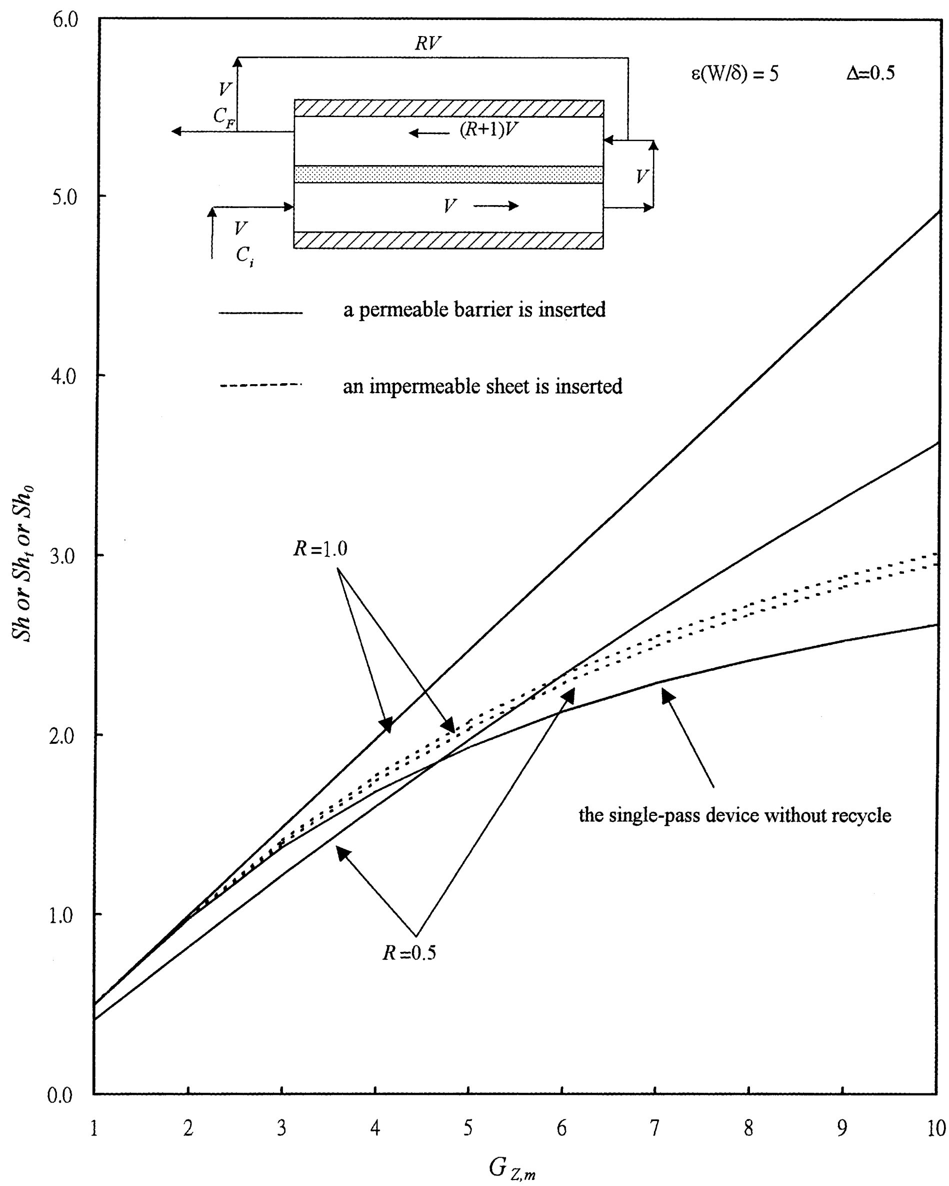

Fig. 4. Average Sherwood number of three devices vs. Gz_m with reflux ratio as a parameter ($\Delta = 0.5$).

tion ($\theta_{F,t}$, θ_F and $\theta_{0,F}$) decreases with increasing the mass Graetz number Gz_m owing to the short residence time of fluid, but increases as the reflux ratio R increases due to the premixing effect and with $\varepsilon(W/\delta)$ decreasing due to mass transfer resistance. The values of parameters, $\varepsilon(W/\delta)$, chosen for the numerical calculations are some illustrations for theoretical results, the appropriate values of those parameters (ε, W and δ) may be selected for the practical application. Moreover, the higher convective mass-transfer coefficient will be created when the ratio of channel thickness Δ diverges from 0.5, especially for $\Delta < 0.5$, that is, in channel 'a' where the concentration difference between the concentrated plate and fluid is larger than that in channel 'b', and hence, the improvement of transfer efficiency is obtainable in such devices. It is found from Tables 1 and 2 that the improvement in the mass transfer coefficient of a double-pass device with external refluxes, based on that of a single-pass device of same dimensions and fluid flow rate without recycle, increases with the mass Graetz number and reflux ratio, as well as with the ratio of thickness Δ diverging from 0.5, especially for $\Delta < 0.5$ by inserting a permeable barrier. Fig. 4 shows the theoretical average Sherwood number (Sh_t, Sh and Sh_0) versus Gz_m with the reflux ratio as a parameter for $\Delta = 0.5$ while Fig. 5 with the ratio of channel thickness Δ as a parameter. It is seen in Figs. 4 and 5 that (Sh_t, Sh and Sh_0) increases with increasing R, but with Δ diverging from 0.5, especially for $\Delta < 0.5$, because k_m, $k_{m,t}$ and $k_{0,m}$ will be enhanced as the fluid velocity increased. The mass transfer coefficient in a double-pass operations Sh is higher than that in a single-pass operations Sh_0, this is because the path length, therefore, the flow rate and the mass-transfer rate are increased when a double-pass operation is employed.

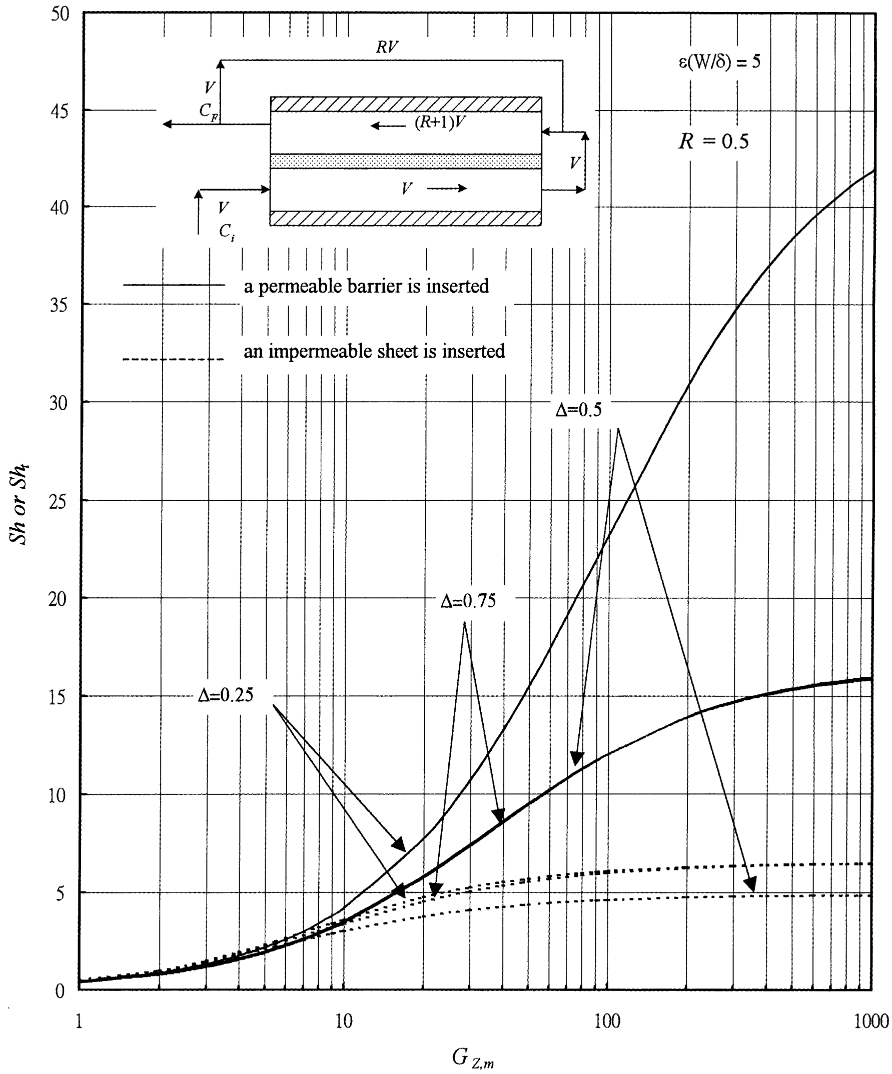

Fig. 5. Average Sherwood number both double-pass devices vs. Gz_m with Δ as a parameter ($R = 0.5$).

The effect of Δ on Sh is also shown in Fig. 5. The reason why $\Delta < 0.5$ is better than $\Delta > 0.5$, for obtaining higher transfer coefficient, is that the mass transfer in the lower channel is more effective than that in the upper channel due to the larger concentration difference. Therefore, decreasing the thickness W_a of the lower channel will increase the fluid velocity v_a, leading to improved performance. Further, the comparison of dimensionless average outlet concentration ($\theta_{F,t}$ and θ_F) as well as average Sherwood number (Sh_t and Sh) in the recycled double-pass devices with permeable barrier or impermeable sheet inserted and in the previous work [10], may be observed from Fig. 6. One may notice in this figure that the values of $\theta_{F,t}$ are higher than θ_F and that in the device in the previous work for large mass Graetz number, say $Gz_m > 20$.

The increment of power consumption I_p due to the friction losses ($\ell w_{f,a}$ and $\ell w_{f,b}$ for double pass while $\ell w_{f,0}$ for single pass) in the conduits with the laminar flow assumed can readily derived as in the previous work [10]:

$$I_p = \frac{(\ell w_{f,a} + \ell w_{f,b}) - (\ell w_{f,0})}{\ell w_{f,0}} = \frac{1}{\Delta^3} + \frac{R+1}{(1-\Delta)^3} - 1 \quad (32)$$

It is readily obtained from Eq. (32) that I_p does not depend on mass Graetz number and increases with reflux ratio as well as with Δ diverging from 0.5, and some results for I_p with R as a parameter are presented in Table 5.

Table 5
The increment of power consumption with reflux ratio and barrier position as parameters

R	I_p		
	$\Delta = 0.25$	$\Delta = 0.5$	$\Delta = 0.75$
0.1	65.61	15.80	71.77
0.5	66.56	19.00	97.37
1.0	67.74	23.00	129.37
5.0	77.22	55.00	385.37

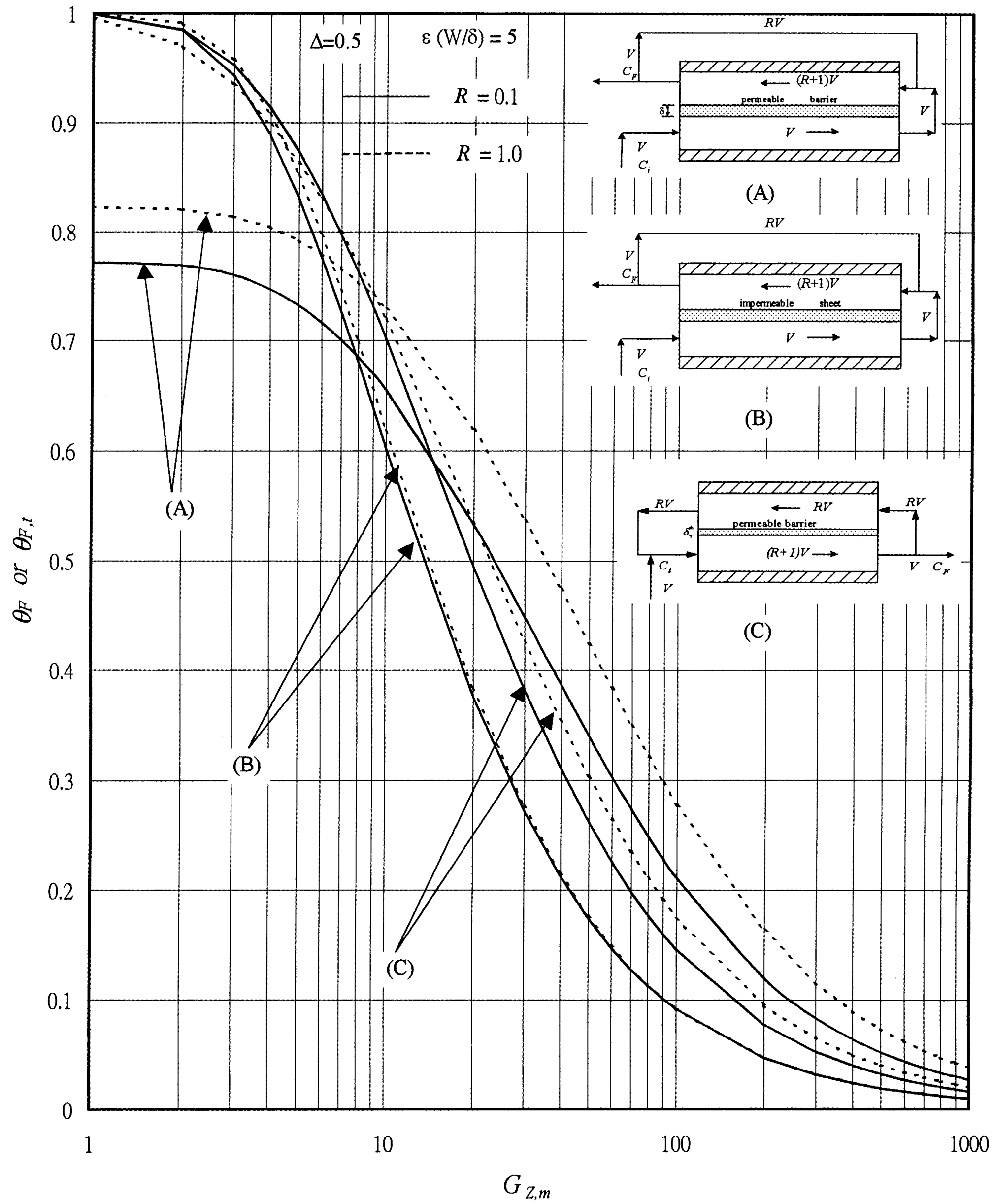

Fig. 6. Dimensionless average outlet concentration of both double-pass devices in the present work and in the previous work [10] vs. Gz_m with R as a parameter ($\Delta = 0.5$).

6. Conclusion

Mass transfer through a double-pass parallel-plate exchanger with inserting a permeable barrier or an impermeable sheet has been investigated analytically. The $\varepsilon(W/\delta)$, R and Δ are three practical parameters in analyzing the mass transfer enhancement of double-pass laminar countercurrent mass exchangers with external refluxes and inserting a permeable barrier or an impermeable sheet, and some results have been calculated and presented in Figs. 2–5, as well as in Tables 1 and 2 with $\varepsilon(W/\delta)$, R and Δ as parameters. Sherwood numbers and, hence, the improvement of mass-transfer efficiencies are proportional to θ_F ($\theta_{F,t}$ or $\theta_{0,F}$), as shown in Eqs. (27)–(31). For small mass Graetz number, no improvement in transfer efficiency can be achieved in the double-pass device with a permeable barrier inserted. Under this region, the double-pass device with inserting an impermeable sheet is preferred to be employed rather than using the double-pass one with a permeable barrier inserted or single-pass devices operating at such conditions. The higher improvement of performance is really obtained by employing a double-pass device with a permeable barrier inserted, instead of using double-pass devices with an impermeable sheet, and single-pass devices for large mass Graetz number, as shown in Figs. 4 and 5. It should be mentioned that the improvement turns to be negative when the mass Graetz number is sufficiently small, as shown by the negative signs in Table 2. This result is also indicated in Figs. 2 and 3 for dimensionless outlet concentrations of double-pass devices with inserting a permeable barrier are higher than those for double-pass devices with an impermeable sheet and single-pass devices for $Gz_m > 10$. It is also shown in Figs. 3 and 5 that the impermeable-sheet (or permeable-barrier) position has much influence on the outlet concentration $\theta_{\mathrm{F,t}}$ (or θ_{F}) as well as Sh_{t} (or Sh), so $\theta_{\mathrm{F,t}}$, and Sh_{t} (or θ_{F} and Sh) increase as the ratio of the thickness Δ diverges from 0.5, especially for $\Delta < 0.5$ by inserting a impermeable-sheet (or permeable-barrier).

Two case studies were given for the improvement of transfer efficiency and the results are shown in Tables 3 and 4. For large L or small V, the residence time is large enough and the reflux effect is no more important, therefore, $I_{m,\mathrm{t}}$ decreases as we proceed down Tables 3 and 4. The minus signs in Table 4 indicate that, no improvement in mass transfer can be achieved at low mass-transfer Graetz number, and in this case, the device without recycle is preferred to be employed rather than using the device with recycle operating at such conditions. The present paper is actually the extension of other recycle problems carried out in the previous work [10], except that the type of reflux. Fig. 6 illustrated some results obtained in the previous work [10] with the same parameter values used in Fig. 2 for comparison. With this comparison, the advantage of present results is evident with large mass Graetz number for the double-pass devices with inserting permeable barrier. It is concluded in Figs. 2–5 that the recycle effect can enhance mass transfer for the fluid flowing through a mass exchanger under double-pass operations by inserting an impermeable sheet for low mass Graetz number or by inserting a permeable barrier with large mass Graetz number, and the concept of recycle effect in designing double-pass mass exchangers is technically and economically feasible.

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