

Effect of External Recycle on the Performance in Parallel-Flow Rectangular Heat-Exchangers

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Abstract

The analysis of heat transfer in the heat exchangers of cocurrent and countercurrent flows with external recycle, has been carried out by heat-transfer theory. Considerable improvement is achievable by recycle operation if the increase in heat-transfer coefficient by applying the recycle effect to enhance the fluid velocity, can compensate for the decrease in the driving force (temperature difference) of heat transfer due to the remixing of inlet fluid. As expected, the heat-transfer rate obtained in the countercurrent-flow heat exchangers with or without recycle are superior to those in the cocurrent-flow devices. However, the space for the improvement in performance by recycle in the countercurrent-flow device is smaller than that in the cocurrent-flow one.

Key Words: Heat Exchanger, External Recycle, Parallel Flow

1. Introduction

Heat exchange between two fluid is one of the most important and frequently used processes in engineering. In the customary type of heat exchangers, two fluids of different temperature flow in spaces separated by a heat-transfer medium, and they exchange heat by convection at and conduction through the medium. The heat exchangers may be extremely different in design and construction, but in principle the only differences are those of relative direction of the two fluids. Accordingly, distinction is made between parallel flow and cross flow. The two fluid in parallel flow may be cocurrent or countercurrent while the direction of two fluids in cross flow may generally be different by 90 angular degrees.

Applications of the recycle-effect concept to the design and operation of heat and mass exchangers with external or internal refluxes can effectively increase in fluid velocity and enhance the transfer coefficient, leading to improved performance [1–8]. Actually, applying the recycle operation to heat and mass exchangers results in

two conflicting effects: the desirable increase in transfer coefficients and the undesirable decrease in driving force due to remixing. It is the purpose of this work to investigate the influence of the external-recycle effect on the performance in a parallel-flow flat-plate heat exchanger.

2. Theory

2.1 Heat-Transfer Coefficients

The schematic diagram in Figure 1 may serve to explain the nomenclature to be employed for cocurrent-and countercurrent-flow heat exchangers with external recycle. These devices are perfectly insulated except of a separating sheet through which heat is exchanged perpendicular to its exposed surfaces. During operation, fluids a and b of different temperature flow in channels a and b, respectively, with external recycle in channel a. The assumptions made in this analysis are: (1) steady state; (2) uniform temperatures, $t_a(x)$ and $t_b(x)$, and velocities, v_a and v_b , over the cross-section (channel width $B \times$ channel height H) of parallel flow; constant rates of flow ($q_a = v_aBH$ and $q_b = v_bBH$) and constant heat-transfer coefficients (U , h_a , h_b and h_w). The overall heat transfer coeffi-

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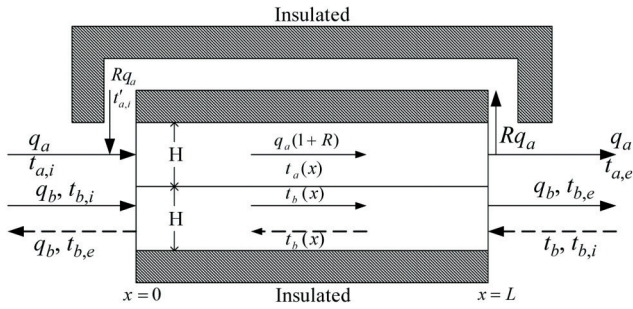


Figure 1. Parallel-flow flat-plate heat exchangers with length L and width B .

coefficient U is related with the average heat transfer coefficients h_a and h_b , in the respect channel and that, h_w , within the separated wall as

$$\frac{1}{U} = \frac{1}{h_a} + \frac{1}{h_w} + \frac{1}{h_b} \quad (1)$$

Since heat transfer within the solid wall is due to conduction alone, the following expression may be used for calculating the heat transfer coefficient in the wall

$$h_w = \frac{k_w}{d} \quad (2)$$

where k_w is the thermal conductivity of the solid wall and d denotes the thickness of wall. Since the heat transfers in both channels are convective, h_a and h_b are functions of fluid properties (thermal conductivity k , density ρ , viscosity μ , specific heat c_p), flow pattern (velocity v , channel width B , channel height H , channel length L), etc. For laminar flows in channels a and b [9,10].

$$h = 1.86(k/D_{eq})(\text{Re Pr } D_{eq}/L)^{1/3} \quad (3)$$

and for turbulent flows [10]

$$h = 0.026(k/D_{eq}) \text{Re}^{0.8} \text{Pr}^{1/3} \quad (4)$$

where the equivalent diameters of both channels are

$$D_{eq} = \frac{4BH}{2(B+H)} \quad (5)$$

while Pr denotes the Prandtl number ($\mu c_p/k$) and Re is the Reynolds number ($D_{eq} v \rho / \mu = D_{eq} q_a \rho / BH \mu$).

2.2 Outlet Temperatures in the Devices without Recycle

Figure 1 illustrates the heat exchange in parallel-flow rectangular heat exchanger without recycle ($R = 0$). A heat balance for the fluid in channel a of a differential length dx :

$$-\dot{m}_a dt_a = UB(t_a - t_b) dx \quad (6)$$

Similarly, in channel b:

$$\dot{m}_b dt_b = UB(t_a - t_b) dx, \text{ cocurrent flow} \quad (7)$$

$$\dot{m}_b dt_b = -UB(t_a - t_b) dx, \text{ countercurrent flow} \quad (8)$$

where the time rate heat capacities are defined by

$$\dot{m}_a = q_a \rho_a c_{p,a} \quad (9)$$

$$\dot{m}_b = q_b \rho_b c_{p,b} \quad (10)$$

Define the following dimensionless groups:

$$\zeta_a = \frac{t_{a,i} - t_a}{t_{a,i} - t_{b,i}} \quad (11)$$

$$\zeta_b = \frac{t_{b,i} - t_b}{t_{a,i} - t_{b,i}} \quad (12)$$

$$n = US/m_a = UBL/m_a \quad (13)$$

$$\ell = US/m_b = UBL/m_b \quad (14)$$

$$\xi = x/L \quad (15)$$

Substitution of Eqs. (11)–(15) into Eqs. (6)–(8) gives

$$n(\zeta_a - \zeta_b + 1) = -(d\zeta_a/d\xi) \text{ both flows} \quad (16)$$

$$\ell(\zeta_a - \zeta_b + 1) = d\zeta_b/d\xi \text{ cocurrent flow} \quad (17)$$

$$\ell(\zeta_a - \zeta_b + 1) = -(d\zeta_a/d\xi) \text{ countercurrent flow} \quad (18)$$

2.2.1 Cocurrent Flow

The temperature distributions of fluids a and b for cocurrent-flow systems can be obtained by solving Eqs.

(16) and (17) simultaneously with the use of the following boundary conditions:

B.C.1 and 2:

$$\zeta_a = \zeta_b = 0 \quad \text{at } \xi = 0 \quad (19)$$

The results are

$$\zeta_a = -(n/\ell)\zeta_b \quad (20)$$

$$= [n/(n+\ell)][1 - e^{-(n+\ell)\xi}] \quad (21)$$

The outlet temperature are then obtained by substituting the conditions: $\zeta_a = \zeta_{a,e}$ and $\zeta_b = \zeta_{b,e}$ at $\xi = 1$, into Eq. (21)

$$\zeta_{a,e} = -(n/\ell)\zeta_{b,e} \quad (22)$$

$$= [n/(n+\ell)][1 - e^{-(n+\ell)}] \quad (23)$$

where

$$\zeta_{a,e} = \frac{t_{a,i} - t_{a,e}}{t_{a,i} - t_{b,i}} \quad (24)$$

$$\zeta_{b,e} = \frac{t_{b,i} - t_{b,e}}{t_{a,i} - t_{b,i}} \quad (25)$$

It is obviously seen from Eq. (23) that both $\zeta_{a,e}$ and $\zeta_{b,e}$ are functions of n and ℓ only, and that though these outlet temperatures depend on the overall heat-transfer area $S (= BL)$ but do not depend either on the length L , or on the width B , of a heat-transfer wall.

2.2.2 Countercurrent Flow

The temperature distributions of the fluids in flow channels a and b for countercurrent-flow systems can be obtained by solving Eqs. (16) and (18) simultaneously with the use of following boundary conditions:

B.C.3:

$$\zeta_a = 0 \quad \text{at } \xi = 0 \quad (26)$$

$$\zeta_b = 0 \quad \text{at } \xi = 1 \quad (27)$$

The results are

$$\zeta_a = [1 - e^{(\ell-n)\xi}] / [1 - (\ell/n)e^{(\ell-n)}] \quad (28)$$

$$\zeta_b = [e^{(\ell-n)} - e^{(\ell-n)\xi}] / [(n/\ell) - e^{(\ell-n)}] \quad (29)$$

The outlet temperatures are than obtained by substituting the conditions: $\zeta_a = \zeta_{a,e}$ at $\xi = 1$ and $\zeta_b = \zeta_{b,e}$ at $\xi = 0$, into Eqs. (28) and (29), i.e.

$$\zeta_{a,e} = -(n/\ell)\zeta_{b,e} \quad (30)$$

$$= [1 - e^{(\ell-n)}] / [1 - (\ell/n)e^{(\ell-n)}] \quad (31)$$

It is also seen from Eqs. (30) and (31) that $\zeta_{a,e}$ and $\zeta_{b,e}$ depend on S but not on either L or B . Further, the relation between the outlet temperatures of two fluids in countercurrent flow is the same as that in cocurrent flow, as shown in Eqs. (20) and (30).

2.2.3 Outlet Temperatures

Once the dimensionless outlet temperatures, $\zeta_{a,e}$ and $\zeta_{b,e}$, are obtained from Eqs. (23) and (31), the outlet temperatures are readily estimated from Eqs. (24) and (25), i.e.

$$t_{a,e} = t_{a,i} - (t_{a,i} - t_{b,i})\zeta_{a,e} \quad (32)$$

$$t_{b,e} = t_{b,i} - (t_{a,i} - t_{b,i})\zeta_{b,e} \quad (33)$$

2.3 Outlet Temperatures in the Devices with External Recycle

As indicated in Figure 1, the dimensionless outlet temperatures for cocurrent and countercurrent devices with recycle are readily obtained from those without recycle, Eqs. (23) and (31), by replacing \dot{m}_a and $t_{a,i}$ with $\dot{m}_a(1+R)$ and $t'_{a,i}$ (mixed temperature at the inlet), respectively. The result is

$$\zeta'_{a,e} = \zeta_{a,e} \Big|_{q_a \rightarrow q_a(1+R)} \quad (34)$$

where

$$\zeta'_{a,e} = \frac{t'_{a,i} - t_{a,e}}{t'_{a,i} - t_{b,i}} \quad (35)$$

and $\zeta_{a,e}$ is defined by Eq. (23) for cocurrent flow, or by Eq. (31) for countercurrent flow.

Since $t'_{a,i}$ is unknown in a prior, an additional energy balance is required at the inlet of the heat exchangers, i.e.

$$t_{a,i} + R t_{a,e} = (1+R)t'_{a,i} \quad (36)$$

Substitution of Eq. (36) into Eq. (35) to eliminate $t'_{a,i}$ yields the outlet temperatures for fluid a in both cocurrent-flow and countercurrent-flow devices with recycle as

$$t_{a,e} = \frac{t_{a,i}(1/\zeta'_{a,e} - 1) + (1+R)t_{b,i}}{R + 1/\zeta'_{a,e}} \quad (37)$$

It is noted that Eq. (37) reduces to Eq. (32) if $\zeta'_{a,e}$ is replaced by $\zeta_{a,e}$ with $R = 0$ for the devices without recycle.

2.4 Heat Transfer Rate

The total heat-transfer rates for both flow-type heat exchangers with or without recycle, can be calculated from an energy balance over the entire heat exchanger

$$Q = \dot{m}_a(t_{a,i} - t_{a,e}), \text{ for } t_{a,i} > t_{b,i} \text{ and } t_{a,i} > t_{a,e} \quad (38)$$

or

$$Q = \dot{m}_a(t_{a,e} - t_{a,i}), \text{ for } t_{a,i} < t_{b,i} \text{ and } t_{a,i} < t_{a,e} \quad (39)$$

Substituting Eq. (32) into Eqs. (38) and (39), one has the heat-transfer rates for the heat exchangers without recycle as

$$Q_o = \pm \dot{m}_a(t_{a,i} - t_{b,i})\zeta_{a,e} \quad (40)$$

where the use of plus or minus sign depends on whether $t_{a,i} > t_{b,i}$, or $t_{a,i} < t_{b,i}$. Similarly, substitution of Eq. (37) into Eqs. (38) and (39) results in the heat-transfer rates for the heat exchangers with recycle

$$Q = \pm \frac{\dot{m}_a(1+R)(t_{a,i} - t_{b,i})}{R + 1/\zeta'_{a,e}} \quad (41)$$

For the device without recycle, $R = 0$ and $\zeta'_{a,e} = \zeta_{a,e}$, Eq. (41) reduces to Eq. (40).

2.5 Heat-Exchanger Efficiency

The heat exchanger efficiency may be defined as

$$\eta = \frac{\text{actual heat-transfer rate}}{\text{maximum possible heat-transfer rate}}$$

Accordingly,

$$\eta = \frac{Q}{\pm US(t_{a,i} - t_{b,i})} \quad (42)$$

Substitution of Eq. (41) into Eq. (42) results in the heat-exchanger efficiency with recycle

$$\eta = \frac{\dot{m}_a(1+R)}{US(R + 1/\zeta'_{a,e})} \quad (43)$$

Some graphical representations of Eq. (43) are given in Figures 2 and 3. It is seen in these figures that η increases with R . Further, since the effect of recycle operation is really needed for low flow rate in channel a to increase the fluid velocity, the heat-exchanger efficiency increases with reflux ratio more rapidly as \dot{m}_a/\dot{m}_b decreases.

3. Improvement in Performance

The improvement in performance by recycle operation is best calculating the percentage increase in heat exchange based on the device without recycle, i.e.

$$I = \frac{Q - Q_o}{Q_o} = \frac{1+R}{(R + 1/\zeta'_{a,e})\zeta_{a,e}} - 1 \quad (44)$$

3.1 Numerical Example

For the purpose of illustration, let us assign some numerical value for the heat exchange of hot and cold waters as follows:

heat-transfer sheet: stainless steel, $S = BL = (0.2)(1.2) = 0.24 \text{ m}^2$; flow channels a and b: $B = 0.2 \text{ m}$, $H = 0.02 \text{ m}$; fluid temperatures: $t_{a,i}/t_{b,i} = 53.3 \text{ }^\circ\text{C}/26.7 \text{ }^\circ\text{C}$, $60 \text{ }^\circ\text{C}/20 \text{ }^\circ\text{C}$, $64 \text{ }^\circ\text{C}/16 \text{ }^\circ\text{C}$, and vice versa; $t_{av} = 40 \text{ }^\circ\text{C}$, fluid properties [11]: $\rho_a = \rho_b = 994 \text{ kg/m}^3$, $C_{p,a} = C_{p,b} = 4.185 \text{ kJ/kg K}$, $k_a = k_b = 0.629 \text{ W/mK}$, $\mu_a = \mu_b = 6 \times 10^{-4} \text{ kg/ms}$; flow rates: $q_a \times 10^5 = 4, 8, 16 \text{ m}^3/\text{s}$, $q_b \times 10^5 = 4, 8, 16 \text{ m}^3/\text{s}$; overall heat transfer coefficient: $\frac{1}{U} \approx \frac{1}{h_a} + \frac{1}{h_b}$

3.2 Results and Discussion

The heat-transfer rates for the heat exchangers without and with recycle were calculated from Eqs. (40) and

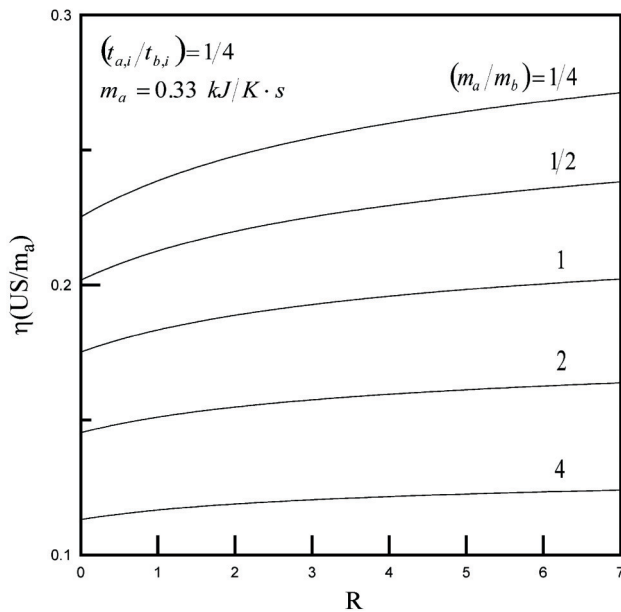


Figure 2. Efficiency of cocurrent-flow heat-exchanger vs. reflux ratio with \dot{m}_a/\dot{m}_b as parameter.

(41), respectively, with the use of above numerical values. Some of them are presented in Tables 1 and 2 for recycle operated in hot ($t_{a,i} > t_{b,i}$) and cold ($t_{a,i} < t_{b,i}$) channels, phase a respectively. The improvements in performance were calculated from Eq. (44) and the results are also presented in the tables for comparison.

3.2.1 Effect of Flow Type on Heat-Transfer Rate

It is seen in Tables 1 and 2 that the heat-transfer rates Q in countercurrent-flow heat exchangers are rather larger than those in cocurrent-flow devices. On the other hand, since the later device has larger space for improving the performance by recycling operation, its improvement I in heat transfer rate is rather bigger than the former device. Further, the efficiencies of both heat exchangers are very close in present illustration, and may approach to the same for higher flow rate and larger reflux ratio.

3.2.2 Effect of Reflux on Performance

Actually, the recycle operation has two conflict effects on performance. The application of recycle operation on heat exchangers not only creates the effect of increase of fluid velocity, leading to enhance overall heat-transfer coefficient, but also lower the temperature difference (heat-transfer driving force) due to the mixing of inlet fluid. At small inlet volume rate q_a the fluid velocity

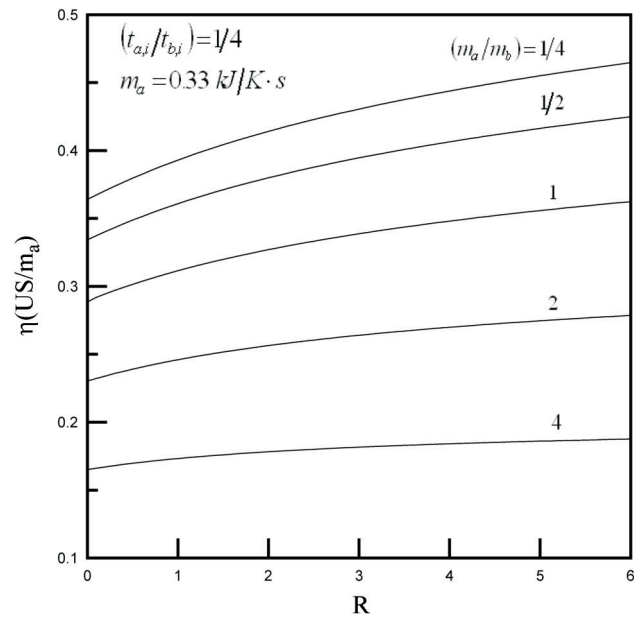


Figure 3. Efficiency of countercurrent-flow heat-exchanger vs. reflux ratio with \dot{m}/\dot{m}_a as parameter.

$v_a (= q_a/BH)$ is small, therefore, the production of increase in fluid velocity created by applying the recycle with reflux ratio R which is not large enough, may not compensate for the situation that the driving force of heat transfer in the heat exchangers decreases. Thus, the heat transfer rate Q in recycle devices of small q_a with low R cannot be over that Q_0 in the devices of the same size but without recycle. Taking a critical case of the given numerical values for instance, if a countercurrent-flow heat exchanger is operated with $q_a = q_b = 2 \times 10^5 \text{ m}^3/\text{s}$, $t_{a,i} = 53.3 \text{ }^\circ\text{C}$ and $t_{b,i} = 26.7 \text{ }^\circ\text{C}$, the performances obtained are $Q_0 = 0.7791 \text{ kJ/s}$ for $R = 0$ and $Q = 0.7597 \text{ kJ/s}$ for $R = 1$. However, the introduction of reflux still has positive effects on heat exchange for larger inlet volume rate. This is due to the increase of fluid velocity having more influence here than the decrease of temperature difference, and the performance in a recycled device is over that in a device of the same size without recycle, as shown in Tables 1 and 2. The improvement increases with the reflux ratio.

3.2.3 Effect of Temperature Difference on Performance

As expected, heat transfer rate increases with the heat-transfer driving force (temperature difference). However, the performances are the same for the cases that the value of $(t_{a,i} - t_{b,i})$ for $t_{a,i} > t_{b,i}$ is equal to the value

Table 1. Heat transfer rates for $t_{a,i} = 53.3$ °C and $t_{b,i} = 26.7$ °C and for $t_{a,i} = 26.7$ °C and $t_{b,i} = 53.3$ °C

$q_a \times 10^5$ (m^3/s)	$q_b \times 10^5$ (m^3/s)	Cocurrent-flow						Counter-current-flow											
		R = 1		R = 3		R = 5		R = 7		R = 1		R = 3		R = 5		R = 7			
		Q	I	Q	I	Q	I	Q	I	Q _o	(kJ/s)	(%)	Q	I	Q	I	Q	I	
4	4	1.0970	1.1230	2.37	1.1616	5.89	1.1863	8.14	1.2039	9.74	1.1287	1.1413	1.12	1.1723	3.86	1.1941	5.79	1.2101	7.21
	8	1.2862	1.3194	2.58	1.3715	6.64	1.4057	9.29	1.4303	11.21	1.3102	1.3336	1.79	1.3801	5.33	1.4120	7.77	1.4354	9.56
	16	1.4462	1.4867	2.80	1.5521	7.32	1.5955	10.32	1.6271	12.51	1.4629	1.4968	2.32	1.5582	6.52	1.6001	9.38	1.6309	11.49
8	4	1.2862	1.3370	3.95	1.3934	8.34	1.4262	10.88	1.4488	12.64	1.3102	1.3512	3.13	1.4017	6.98	1.4322	9.31	1.4536	10.94
	8	1.5505	1.6230	4.68	1.7060	10.03	1.7553	13.21	1.7898	15.43	1.5702	1.6350	4.13	1.7132	9.11	1.7607	12.13	1.7941	14.26
	16	1.7868	1.8820	5.33	1.9936	11.57	2.0610	15.35	2.1086	18.01	1.8013	1.8911	4.99	1.9992	10.99	2.0653	14.65	2.1121	17.25
16	4	1.4464	1.5125	4.57	1.5799	9.10	1.6141	11.61	1.6386	13.30	1.4629	1.5222	4.06	1.5836	8.25	1.6183	10.62	1.6419	12.24
	8	1.7868	1.8879	5.66	1.9911	11.43	2.0495	14.70	2.8094	16.93	1.8013	1.8969	5.30	1.9964	10.83	2.0534	13.99	2.0925	16.17
	16	2.1059	2.2465	6.68	2.3937	13.66	2.4785	17.69	2.5372	20.48	2.1173	2.2537	6.44	2.3981	13.26	2.4819	17.22	2.5399	19.96

Table 2. Heat transfer rates for $t_{a,i} = 64$ °C and $t_{b,i} = 16$ °C and for $t_{a,i} = 16$ °C and $t_{b,i} = 64$ °C

$q_a \times 10^5$ (m^3/s)	$q_b \times 10^5$ (m^3/s)	Cocurrent-flow						Counter-current-flow											
		R = 1		R = 3		R = 5		R = 7		R = 1		R = 3		R = 5		R = 7			
		Q	I	Q	I	Q	I	Q	I	Q _o	(kJ/s)	(%)	Q	I	Q	I	Q	I	
4	4	1.9796	2.0265	2.37	2.0961	5.89	2.1406	8.14	2.1724	9.74	2.0367	2.0595	1.12	2.1154	3.86	2.1547	5.79	2.1836	7.21
	8	2.3209	2.3809	2.58	2.4750	6.64	2.5365	9.29	2.5810	11.21	2.3643	2.4066	1.79	2.4904	5.33	2.5479	7.77	2.5903	9.56
	16	2.6098	2.6828	2.80	2.8007	7.32	2.8791	10.32	2.9362	12.51	2.6398	2.7009	2.32	2.8119	6.52	2.8874	9.38	2.9430	11.50
8	4	2.3209	2.4127	3.95	2.5143	8.34	2.5735	10.88	2.6143	12.64	2.3643	2.4383	3.13	2.5294	6.98	2.5844	9.31	2.6230	10.90
	8	2.7979	2.9287	4.68	3.0784	10.03	3.1675	13.21	3.2297	15.43	2.8334	2.9503	4.13	3.0915	9.11	3.1772	12.10	3.2375	14.30
	16	3.2243	3.3962	5.33	3.5974	11.57	3.7191	15.35	3.8050	18.01	3.2505	3.4126	4.99	3.6077	11.00	3.7268	14.70	3.8113	17.30
16	4	2.6098	2.7291	4.57	2.8473	9.10	2.9127	11.61	2.9569	13.30	2.6398	2.7468	4.06	2.8576	8.25	2.9202	10.60	2.9628	12.20
	8	3.2243	3.4067	5.66	3.5929	11.43	3.6983	14.70	3.7703	16.93	3.2505	3.4227	5.30	3.6026	10.80	3.7054	14.00	3.7760	16.20
	16	3.8001	4.0539	6.68	4.3194	13.66	4.4725	17.69	4.5784	20.48	3.8207	4.0669	6.44	4.3275	13.30	4.4786	17.20	4.5834	20.00

of $(t_{b,i} - t_{a,i})$ for $t_{a,i} < t_{b,i}$. Further, the improvements in performance I in each flow-type device are the same for the six temperature differences employed in present study with the same average fluid temperature, $t_{av} = 40$ °C, as shown in Tables 1 and 2.

4. Conclusion

The theory of heat exchange in parallel-flow flat-plate heat exchangers with external reflux has been developed for cocurrent-flow and countercurrent-flow operations. The performances obtained in such two devices are very close, even with recycle, for the case illustrated in present study. As expected, the performance in countercurrent-flow heat exchanger is rather better than that in cocurrent-flow device. This fact will be more obvious when the devices are operated under higher temperature difference and/or low flow rate and/or smaller reflux ratio.

Considerable improvement in heat transfer is achievable if heat exchange is operated with recycle which provides the increase in fluid velocity, as well as heat-transfer coefficient. The enhancement increases with the reflux ratio R . The heat-exchanger efficiency η is defined and also discussed in section 2.5. with the graphical representations given in Figures 2 and 3. η increases with reflux ratio, and the increment turns more rapidly when \dot{m}_a / \dot{m}_b decreases. This is because that the recycle operation is really needed in the channel with low flow rate. Actually, the recycle operation has two conflicting effects on the heat transfer in heat exchangers. One is the increase in fluid velocity as well as the improvement in heat-transfer coefficient, U , which is good for performance, while the other is lowering the driving force of heat transfer (temperature difference) due to remixing at the inlet, which is bad for performance. In the numerical example given in present study, increase in U by increasing reflux ratio compensate for the decrease in temperature difference, leading to improved performance. For small inlet volume rate (say $q_a = 2 \times 10^{-5}$ m³/s), however, the increase in U by applying the recycle with R which is not large enough (say $R = 1$), cannot compensate for the decrease in temperature difference, as mentioned in section 3.2.2. In this case, one may rather employ the heat exchangers without recycle operation, instead of using the recycled devices.

It should be noted that since the heat-transfer rates (Q) obtained in the countercurrent-flow heat exchangers with or without recycle, are superior to those in the cocurrent-flow device, the space for the improvement (I) by recycle in the countercurrent-flow device is smaller than that in the cocurrent-flow one, as indicated in Tables 1 and 2.

Nomenclature

B	width of flow channel (m)
C_p	specific heat (kJ/kg K)
D_{eq}	equivalent diameter of flow channel (m)
d	thickness of heat-transfer sheet (m)
H	height of flow channel (m)
h	heat transfer coefficient (W/m ² K)
I	improvement in heat transfer rate
k	thermal conductivity of fluid (W/m K)
L	effective length of a heat exchanger (m)
ℓ, n	dimensionless group defined by Eq. (14), Eq. (13)
\dot{m}	time rate of heat capacity, $q \rho C_p$ (kJ/s K)
Pr	Prandtl number ($\mu C_p / k$)
Q	heat-transfer rate (kJ/s)
R	reflux ratio
Re	Reynolds number ($D_{eq} \nu \rho / \mu$)
S	overall heat-transfer area, BL (m ²)
t	fluid temperature (K)
$t_{a,i}$	inlet temperature of fluid flowing in channel a without mixing (K)
U	overall heat-transfer coefficient (W/m ² K)
ν	fluid velocity (m/s)
x	x axis (m)

Greek Letters

ρ	fluid density (kg/m ³)
μ	fluid viscosity (kg/m s)
ζ	normalized fluid temperature change in the flow channel, compared to the maximum possible temperature change, defined by Eqs. (11) and (12)
ζ'	ζ with q_a replaced by $q_a(1 + R)$
ξ	x/L

Subscript

a, b	flow channel a, b
i	inlet
e	outlet

- o the operation without recycle
- w separated wall, heat-transfer sheet

Superscript

- ' mixed

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