Chapter 14
Direct-Contact Gas–Solid Nonstoring Exchangers

In this chapter, we first take up the fluidized bed heat exchanger and then various other devices such as moving grates and moving bed exchangers.

14.1 Fluidized Bed Heat Exchangers: Preliminary Considerations

Consider the fluidized bed of Fig. 14.1 wherein a stream of cold particles and a stream of hot gas enter, exchange heat, and then leave. Let us examine some of the properties of this stream of solids. From these findings we will be in a position to choose a reasonable set of assumptions to represent the gas–solid fluidized bed exchanger.

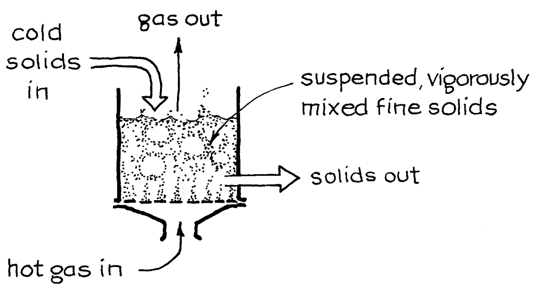

Fig. 14.1 Solids heating in a fluidized bed

1. ΔT *within single particles*. Suppose a particle, initially at T_{s0}, suddenly finds itself in surroundings at T_g. Let us ask how long it would take for the particle to approach the temperature of its surroundings. This we call the thermal relaxation time of the particle.

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As an estimate of the relaxation time, let us determine the time needed for a 90 % approach to equilibrium conditions, of particles of various sizes moving through 100 °C air at 1 m/s. Following the calculation method of Example 11.1, we obtain the values of Table 14.1. Clearly, for particles about $d_p = 1$ mm or smaller, the relaxation time is very small, certainly an order of magnitude smaller than the mean residence time of solids in the vessel.

Table 14.1 Thermal relaxation times for spherical particles passing through air at 1 m/s

	Relaxation time, t			
	$d_p = 100\,\mu$m	$d_p = 1$ mm	$d_p = 10$ mm	$d_p = 100$ mm
Copper	130 ms[a]	7.5 s[a]	320 s[a]	190 min[a]
	(0.03 ms)[b]	(0.003 s)[b]	(0.3 s)[b]	(0.5 min)[b]
Iron	140 ms[a]	7.8 s[a]	330 s[a]	190 min[a]
Stainless steel	140 ms[a]	7.8 s[a]	330 s[a]	190 min[a]
Glass	64 ms[a]	3.7 s[a]	150 s[a]	110 min
Sand	80 ms[a]	4.5 s[a]	240 s	160 min
PVC plastic	56 ms[a]	3.8 s	170 s	150 min
Wood	40 ms[a]	3.4 s	160 s	130 min
Ice	80 ms[a]	4.5 s[a]	190 s[a]	110 min[a]
Na–K (56 % Na)[c]	39 ms[a]	2.2 s[a]	92 s[a]	54 min[a]
Water[c]	160 ms[a]	9.2 s[a]	440 s	290 min

[a]Film resistance controls, Bi < 0.1. All other values in the table fall in the mixed control (particle conduction and film resistance) regime
[b]() Values assuming no film resistance. These values are greatly in error
[c]Assume no circulation in the particle. In the presence of circulation, the relaxation time is much reduced

2. ΔT *among particles*. Because of the large heat capacity of solids (about 1,000 times that of gas, per unit of volume) and because of the rapid circulation of solids in the fluidized bed, we can assume that the particles are uniform in temperature everywhere in the bed.

3. ΔT *between particles and exit gases*. To get a rough order of magnitude estimate of this ΔT, assume plug flow of gas and well-mixed solids in the bed. Referring to Fig. 14.2, a heat balance across the slice of bed of thickness dx then gives

$$-d\dot{q} = \dot{m}_g C_g dT_g = \rho_g u_0 A_t C_g dT_g = hA_{tx}\left(T_g - T_s\right) dx$$

Replacing values, rearranging, and integrating gives

$$\ln \frac{T_{g,\ \text{in}} - T_s}{T_{g,\ \text{out}} - T_s} = \frac{haL}{\rho_g u_0 C_g} = \frac{\text{Nu}_p}{\text{Pr} \cdot \text{Re}_p} \cdot \frac{6\left(1-\varepsilon_f\right)L}{d_p}$$

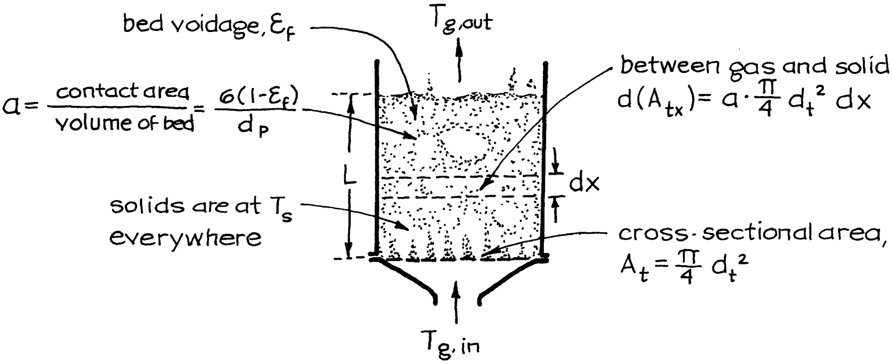


Fig. 14.2 Development of the heat balance between gas and solids in a fluidized bed

Now for a 95 % temperature approach of gas to the temperature of the particles

$$\ln \frac{T_{g,\text{ in}} - T_s}{T_{g,\text{ out}} - T_s} = \ln 20 \geq 3$$

and combining the above two expressions gives

$$\frac{L}{d_p} \geq 0.5 \frac{\text{Pr} \cdot \text{Re}_p}{\text{Nu}_p \left(1 - \varepsilon_f\right)}$$

Typically for 0.5-mm particles we find

$$\frac{L}{d} > 25.6 \text{ or } L > 1.28 \text{ cm}$$

So, for beds deeper than 1 cm, we can reasonably assume that $T_{g,\text{out}} \cong T_s$, and consequently, for beds deeper than this, we can take $h \cong \infty$ between gas and solid or, more properly, $(h_{g\text{–}s}\, a) \cong \infty$.

4. To *summarize* the findings of this preliminary analysis, all particles in a fluidized bed are isothermal and at the same temperature. In addition, gas leaves at the temperature of the bed solids and $(h_{g\text{–}s}a) \cong \infty$. These then are the assumptions which we will use to characterize the behavior of gas–solid fluidized bed heat exchangers.

14.2 Mixed Flow *G*/Mixed Flow *S* or Single-Stage Fluidized Bed Exchangers

Consider the fluidized bed exchanger of Fig. 14.3. A heat balance over the whole unit gives

$$\boxed{-\dot{m}_g C_g \left(T_1 - T_{\text{g, in}}\right) = \dot{m}_s C_s \left(T_1 - T_{\text{s, in}}\right)} \qquad (14.1)$$

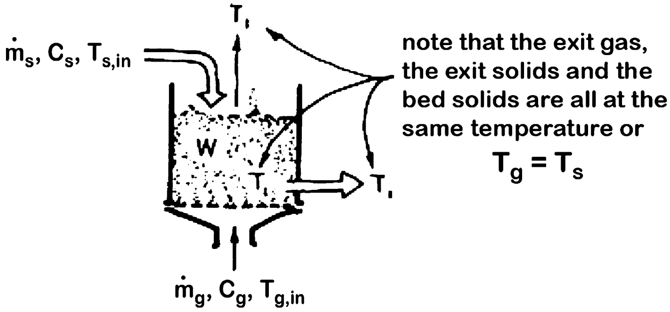


Fig. 14.3 A single-stage fluidized bed heat exchanger with through-flow of gas and solids

Note that no rate equation is used here. This is because we took $(h_{g-s}a) = \infty$. So on rearranging we find

$$T_1 = \frac{T_{s,\text{ in}} + \phi T_{g,\text{ in}}}{1 + \phi} \tag{14.2}$$

where ϕ is the heat flow ratio of the two flowing streams, defined as

$$\phi = \frac{\dot{m}_g C_g}{\dot{m}_s C_s} = -\frac{\Delta T_s}{\Delta T_g} = \frac{W/\dot{m}_s}{\left(1 - \varepsilon_f\right)(L/u_0)} \cdot \frac{\rho_g C_g}{\rho_s C_s} \tag{14.3}$$

The efficiencies of heat utilization are then, from equation (14.2),

$$\left.\begin{aligned} \eta_g &= \frac{\Delta T_g}{\Delta T_{\max}} = \frac{T_{g,\text{ in}} - T_1}{T_{g,\text{ in}} - T_{s,\text{ in}}} = \frac{1}{1+\phi} \\ \eta_s &= \frac{\Delta T_s}{\Delta T_{\max}} = \frac{T_1 - T_{s,\text{ in}}}{T_{g,\text{ in}} - T_{s,\text{ in}}} = \frac{\phi}{1+\phi} = 1 - \eta_g \end{aligned}\right\} \tag{14.4}$$

Efficiencies of heat utilization are always low in single fluidized bed heat exchangers. For example if $\eta = 0.7$ for the gas, it will be 0.3 for the solid (always sum up to 1). To raise the efficiency, we multistage, either crossflow or counterflow. We consider these next.

14.3 Counterflow Stagewise Fluidized Bed Exchangers

Consider N beds of equal size, as shown in Fig. 14.4. A heat balance around each bed gives

$$\left.\begin{aligned} &\text{Bed 1}: & T_1 - T_{s,\text{ in}} &= \phi(T_2 - T_1) \\ &\text{Bed 2}: & T_2 - T_1 &= \phi(T_3 - T_2) \\ &\vdots & \vdots & \quad\quad \vdots \\ &\text{Bed}\,N: & T_N - T_{N-1} &= \phi\left(T_{g,\text{ in}} - T_N\right) \end{aligned}\right\} \tag{14.5}$$

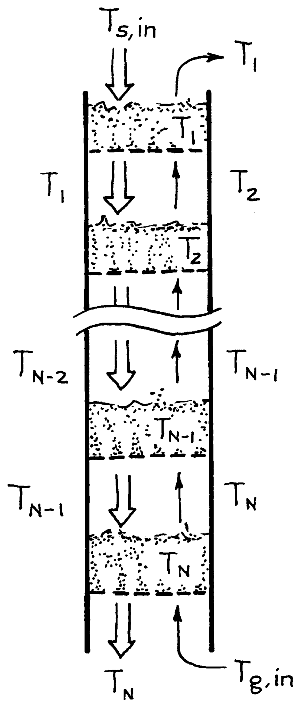


Fig. 14.4 A multistage counterflow fluidized bed heat exchanger

Combining equation (14.5) and eliminating intermediate temperatures give

$$\left.\begin{aligned}\eta_g &= \frac{T_{g,\text{ in}} - T_1}{T_{g,\text{ in}} - T_{s,\text{ in}}} = \frac{\sum_{n=0}^{N-1}\phi^n}{\sum_{n=0}^{N}\phi^n} = \frac{1+\phi+\phi^2+\cdots\phi^{N-1}}{1+\phi+\phi^2+\cdots\phi^{N-1}+\phi^N} \\ \eta_s &= \frac{T_N - T_{s,\text{ in}}}{T_{g,\text{ in}} - T_{s,\text{ in}}} = \frac{\sum_{n-1}^{N}\phi^n}{\sum_{n=0}^{N}\phi^n} = \frac{\phi+\phi^2+\cdots\phi^{N-1}+\phi^N}{1+\phi+\phi^2+\cdots\phi^{N-1}+\phi^N}\end{aligned}\right\} \tag{14.6}$$

Adjusting flow rates so that $\phi = 1$ (if one stream loses 100°, the other gains 100°) gives

$$\eta_g = \eta_s = \frac{N}{N+1} \tag{14.7}$$

For a large number of stages, $N \to \infty$, countercurrent plug flow is approached and

$$\left.\begin{array}{lll} \text{for equal heat flows, or } \phi = 1: & \eta_g = \eta_s = 1 \\ \text{for excess of solids, or } \phi < 1: & \eta_g = 1 \text{ and } \eta_s = \phi \\ \text{for excess of gas, or } \phi > 1: & \eta_g = \dfrac{1}{\phi} \text{ and } \eta_s = 1 \end{array}\right\} \tag{14.8}$$

14.4 Crossflow Stagewise Fluidized Bed Exchangers

Consider N beds of equal size having the same gas flow through each stage, as shown in Fig. 14.5. A heat balance about each bed gives

$$\left.\begin{array}{lll} \text{Bed 1}: & T_1 - T_{s,\text{ in}} = \phi'\left(T_{g,\text{ in}} - T_1\right) \\ \text{Bed 2}: & T_2 - T_1 = \phi'\left(T_{g,\text{ in}} - T_2\right) \\ \vdots & \vdots \quad\quad \vdots \\ \text{Bed } N: & T_N - T_{N-1} = \phi'\left(T_{g,\text{ in}} - T_N\right) \end{array}\right\} \tag{14.9}$$

where ϕ' is based on the heat flow through each stage or

$$\phi' = \frac{\left(\dot{m}_g/N\right)\cdot C_g}{\dot{m}_s C_s} = \frac{\phi_{\text{countercurrent}}}{N} \tag{14.10}$$

Now with equal gas flows through each of the N stages, we have

$$T_{g,\text{ out}} = \frac{T_1 + T_2 + \cdots + T_N}{N} \tag{14.11}$$

Combining equations (14.9) and (14.11) gives the efficiencies of operation as

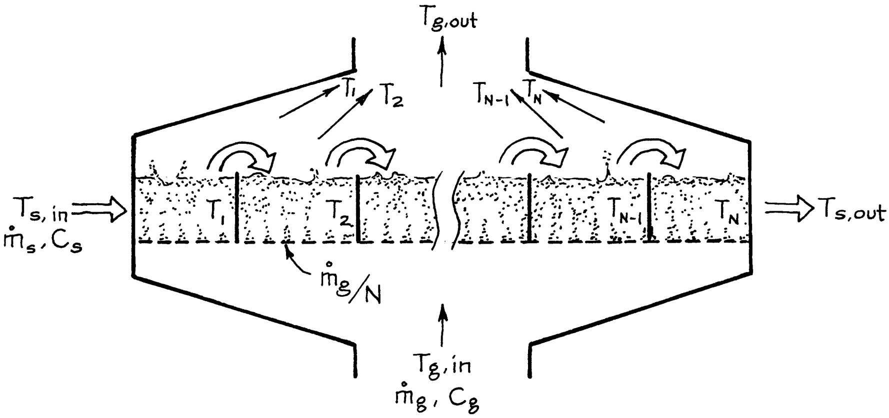


Fig. 14.5 A multistage crossflow fluidized bed heat exchanger

$$\left.\begin{aligned} \eta_g &= \frac{\Delta T_g}{\Delta T_{\max}} = \frac{T_{g,\text{ in}} - T_{g,\text{ out}}}{T_{g,\text{ in}} - T_{s,\text{ in}}} = \frac{1}{N\phi'}\left[1 - \frac{1}{\left(1+\phi'\right)^N}\right] \\ \eta_s &= \frac{\Delta T_s}{\Delta T_{\max}} = \frac{T_N - T_{\text{s, in}}}{T_{g,\text{ in}} - T_{s,\text{ in}}} = \left[1 - \frac{1}{\left(1+\phi'\right)^N}\right] = N\phi'\eta_g \end{aligned}\right\} \quad (14.12)$$

Comparing crossflow and counterflow operations shows that for any number of stages, N counterflow has the advantage of being more efficient thermally. However, counterflow has the drawbacks of higher pressure drop, more hydraulic problems, especially with downcomers, and more mechanical design complications.

14.5 Countercurrent Plug Flow Exchangers

This contacting pattern, see Fig. 14.6, approximates moving bed and shaft kiln operations, and its Q versus T diagram is shown in Fig. 14.7.

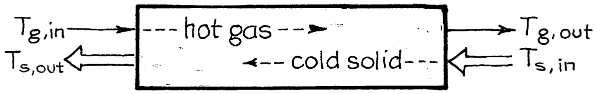


Fig. 14.6 Countercurrent gas–solid contacting

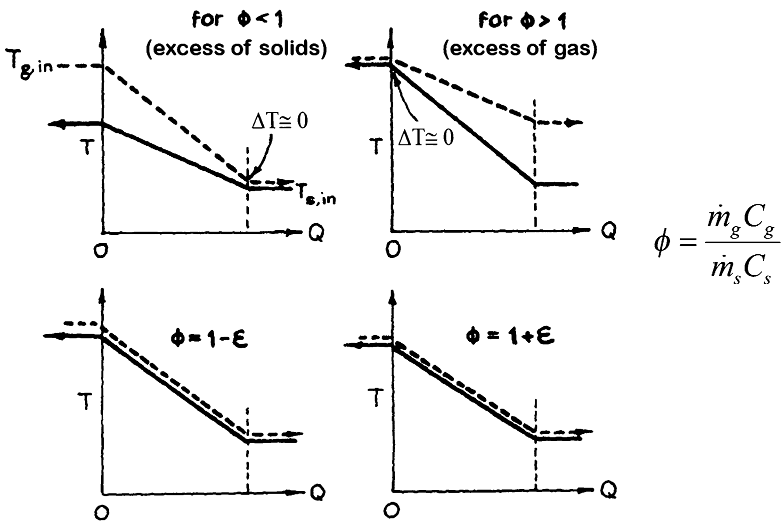


Fig. 14.7 Q vs. T diagram for countercurrent plug flow of gas and solid wherein $(h_{g-s}a) = \infty$

With a stream of small particles, the surface area of contact is large, and the particle relaxation time is short compared to the time of passage of particles through the exchanger (see Sect. 14.1 of this chapter). The behavior of such systems is equivalent to having a very large ($h_{g-s}a$) value, approaching infinity. This means that all the heat exchange takes place in a very narrow zone of the exchanger. Consequently, the temperature versus distance diagram for this operation is as sketched in Fig. 14.8. Note that for close to equal heat flow rates, or $\phi \cong 1$, the location of the temperature front is uncertain. With a slight excess of solids ($\phi = 1 - \varepsilon$), the front slowly migrates to the gas inlet, point A in Fig. 14.8. With a slight excess of gas, it slowly migrates to the solid inlet, point B in Fig. 14.8.

Compare the corresponding sketches of Figs. 14.7 and 14.8 to satisfy yourself that they make sense.

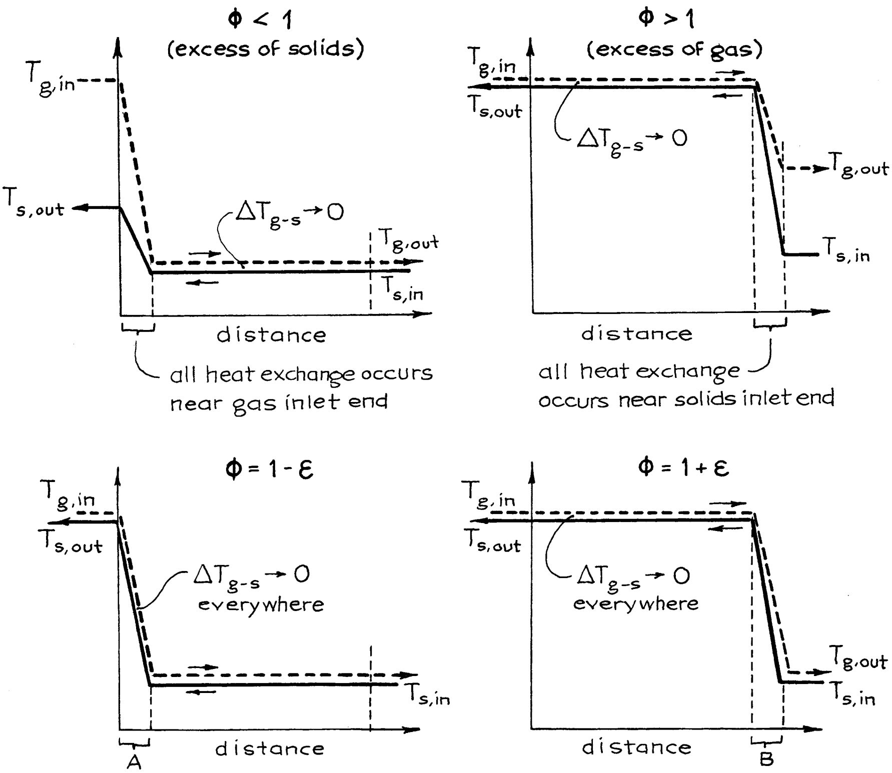


Fig. 14.8 Temperature profiles for countercurrent plug flow of gas and solid. For small particles, all heat exchange takes place near one or other end of the exchanger

A heat balance over the whole exchanger gives

$$\left.\begin{array}{lll} \text{for equal heat flows, or } \phi = 1: & \eta_g = \eta_s = 1 \\ \text{for an excess of solids, or } \phi < 1: & \eta_g = 1 \text{ and } \eta_s = \phi \\ \text{for an excess of gas, or } \phi > 1: & \eta_g = \dfrac{1}{\phi} \text{ and } \eta_s = 1 \end{array}\right\} \tag{14.13}$$

Comments

1. These expressions show that the stream with lower heat flow achieves 100 % heat utilization; the stream in excess does not.
2. For very small particles the heat exchange zone is very narrow, and the temperature of gas and solid is very close to each other nearly everywhere. For larger particles the heat exchange zone broadens, and for very large particles one may have to account for nonuniformity in temperature within particles. This type of problem can be treated by a direct extension of the analysis of Chap. 15.

14.6 Crossflow of Gas and Solids

The way we analyze this contacting pattern depends on the temperature distribution of the flowing solids. There are three extremes that we may want to consider. In all of these cases, we assume a relatively short relaxation time or $(h_{g\text{–}s}a) \to \infty$.

14.6.1 Well-Mixed Solids/Plug Flow Gas

The analysis is analogous to that in Sect. 13.V with UA replaced by ha. And for $ha \to \infty$, equations (13.29) and (13.30) reduce to

$$\left.\begin{array}{l} T_{g,\text{ out}} = T_{s,\text{ out}} = \dfrac{\dot{m}_g C_g T_{g,\text{ in}} + \dot{m}_s C_s T_{s,\text{ in}}}{\dot{m}_g C_g + \dot{m}_s C_s} \\ \eta_g = \dfrac{1}{\phi + 1} \\ \eta_s = \dfrac{\phi}{\phi + 1} \end{array}\right\} \tag{14.14}$$

Fluidized beds of large particles approximate this extreme.

14.6.2 Solids Mixed Laterally but Unmixed Along Flow Path/Plug Flow Gas

This extreme is representative of a thin stream of solids being contacted crosswise by gas, as shown in Fig. 14.9.

This contacting pattern is identical to the crossflow stagewise fluidized bed exchanger, treated in Sect. 14.4, but with an infinite number of stages. So letting $N \to \infty$ as $\phi' \to 0$ in equation (14.12) gives

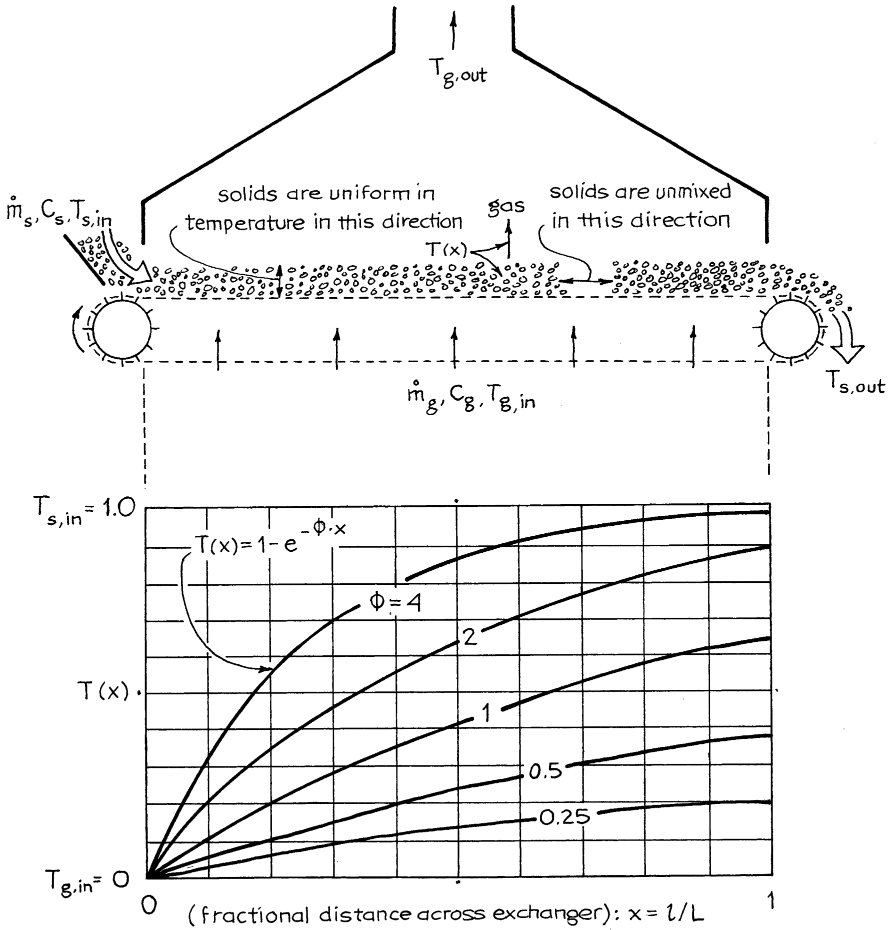


Fig. 14.9 Crossflow exchanger with a thin layer of solids and its temperature distribution at various gas–solid flow ratios, ϕ

$$\left.\begin{aligned}\eta_g &= \frac{\Delta T_g}{\Delta T_{g,\ \max}} = \frac{1}{\phi}\left[1 - e^{-\phi}\right] \\ \eta_s &= \frac{\Delta T_s}{\Delta T_{s,\ \max}} = 1 - e^{-\phi}\end{aligned}\right\} \tag{14.15}$$

14.6.3 Solids Unmixed/Plug Flow Gas

This extreme represents a thick stream of solids contacted crosswise by gas, as shown in Fig. 14.10. For plug flow of both hot gas and cold solids, a sharp temperature front exists as shown in Fig. 14.11; thus, the efficiency of heat utilization is

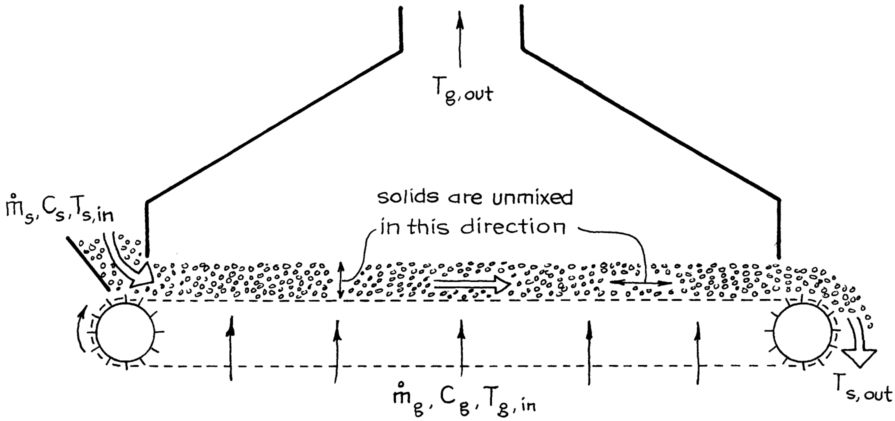


Fig. 14.10 Crossflow exchanger with a thick layer of solids (unmixed vertically)

$$\left.\begin{aligned}&\text{for excess of solids, } \phi < 1: \quad \eta_g = 1 \text{ and } \eta_s = \phi \\ &\text{for excess of gas, } \phi > 1: \quad \eta_g = \frac{1}{\phi} \text{ and } \eta_s = 1\end{aligned}\right\} \tag{14.16}$$

14.7 Comments

The whole treatment of this chapter assumes a short temperature relaxation time for the solids. This assumption is quite reasonable for fluidized beds of fine particles with their very large surface-to-volume ratios.

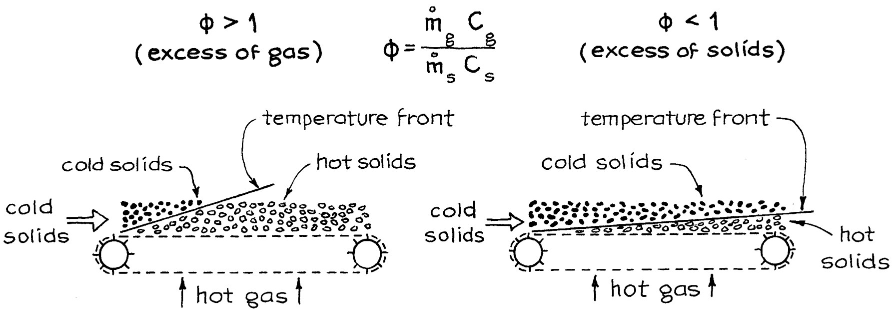


Fig. 14.11 Temperature distribution in a crossflow exchanger with a thick layer of solids and $(h_{g-s}a) = \infty$

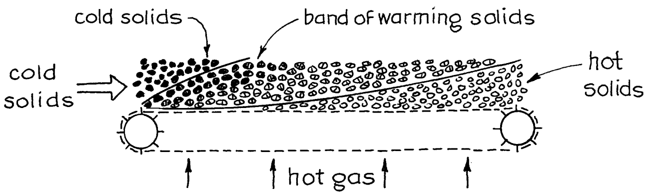


Fig. 14.12 Crossflow heating of a stream of large particles for which $(h_{g-s}a)$ is small

However, conveyor belts and moving beds of solids often are used to heat or cool streams of large particles. These do not respond rapidly to temperature changes, as is clearly shown in Table 14.1. In addition, gas dispersion and backmixing in these large particle systems can result in serious deviations from plug flow for the gas. Both these factors cause a blurring and broadening of the temperature front in these exchangers, as sketched in Fig. 14.12.

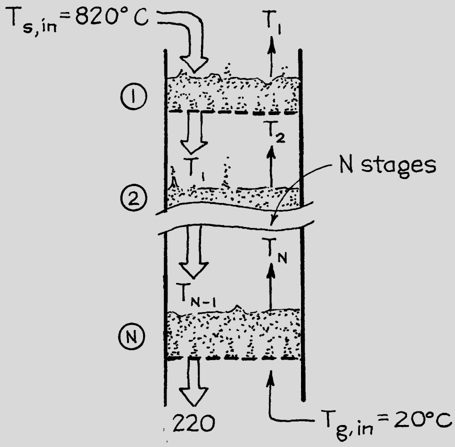
The extent of this broadening depends on the temperature relaxation time of the solids and the extent of gas dispersion compared to the residence time of gas and solid in the gas–solid exchanger. This effect is strongly affected by an increase in particle size. The analysis of this situation is not easy but can be developed following the analysis of Chap. 15.

Example 14.1 Counterflow Multistage Fluidized Bed Exchanger
We plan to cool a continuous stream of hot solids from 820 °C to 220 °C with cold gas at 20 °C in staged counterflow fluidized beds.

(a) Determine the number of stages needed; see drawing below.
(b) Find the temperature of the flowing streams in the exchanger.

(continued)

(continued)



Data. Adjust the flow rates of gas and solid so as to obtain the same thermal utilization for the two streams, or $\eta_g = \eta_s$, or $\phi = 1$.

Solution

(a) From the information for the stream of solids:

$$\eta_s = \frac{\Delta T_s}{\Delta T_{s,\max}} = \frac{220 - 820}{20 - 820} = 0.75$$

For equal thermal utilization, $\eta_s = \eta_g$, equation (14.7) gives

$$0.75 = \frac{N}{N+1}$$

Thus, the number of stages required is

$$\boxed{N = 3}$$

(b) For the gas stream:

$$\eta_g = 0.75 = \frac{\Delta T_g}{\Delta T_{g,\ \max}} = \frac{T_1 - 20}{820 - 20}$$

(continued)

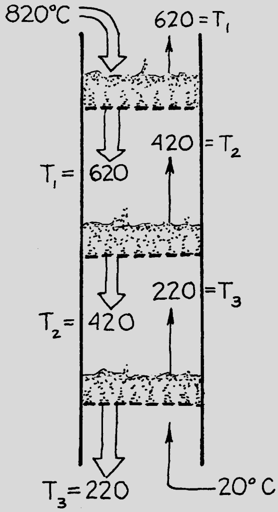
Hence, the exit gas temperature

$$T_1 = 620^\circ\text{C}$$

Equation (14.5) then gives the temperature distribution within the exchanger. Thus, with $\phi = 1$,

$$620 - 820 = 1\ (T_2 - 620) \quad \text{or} \quad T_2 = \boxed{420^\circ\text{C}}$$
$$420 - 620 = 1\ (T_3 - 420) \quad \text{or} \quad T_3 = \boxed{220^\circ\text{C}}$$

Thus, the final sketch is shown below.



Example 14.2 Crossflow Multistage Fluidized Bed Exchanger
Repeat Example 14.1 with just one change—use a crossflow rather than a counterflow exchanger; see below.

(continued)

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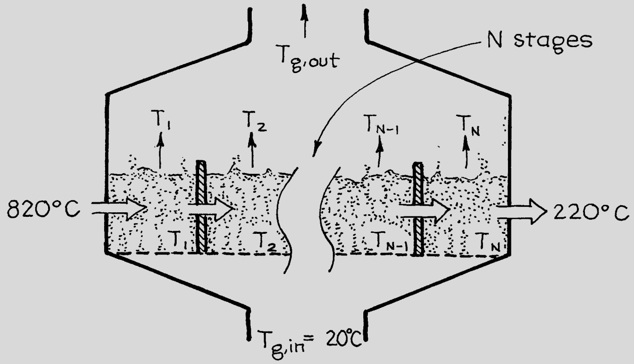


Solution
For equal thermal utilization we have, as with Example 14.1,

$$\eta_s = 0.75, \quad \eta_g = 0.75, \quad -\frac{\Delta T_g}{\Delta T_s} = 1, \; \frac{\dot{m}_g C_g}{\dot{m}_s C_s} = 1$$

Now since ϕ' refers to the flow through each stage,

$$\phi' = \frac{(\dot{m}_g/N)C_g}{\dot{m}_s C_s} = \frac{1}{N}\cdot\frac{\dot{m}_g C_g}{\dot{m}_s C_s} = \frac{1}{N}$$

Then, equation (14.12) gives

$$\eta_s = 0.75 = 1 - \frac{1}{(1+\phi')^N} = 1 - \frac{1}{[1+(1/N)]^N}$$

or

$$\left(\frac{N+1}{N}\right)^N = 4$$

(continued)

Solve by trial and error:

Guess N	$\left(\frac{N+1}{N}\right)^N$
1	2
3	2.37
9	2.58
99	2.70

The above progression does not seem to be able to reach the desired value of "4." We verify this suspicion by examining the limit or

$$\lim_{N\to\infty}\left(\frac{N+1}{N}\right)^N = \lim_{N\to\infty}\left(1+\frac{1}{N}\right)^N = e = 2.718$$

This shows that one cannot get a solution to equation (ii). This means that

It is impossible to get the required 75 % heat utilization in any crossflow exchanger, even though this can be done in 3-slage counterflow exchangers.

Problems on Direct-Contact Gas–Solid Nonstoring Exchangers

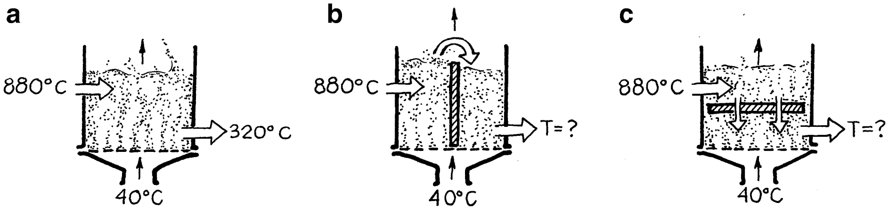
14.1. A stream of fine solids is to be cooled from 820 °C to 100 °C by cold gas heating from 20 °C to 500 °C in a counterflow multistage fluidized bed exchanger. How many ideal stages are needed?

14.2. A crossflow multistage fluidized bed exchanger is to cool a stream of fine solids from 820 °C to 220 °C by contact with gas which heats from 20 °C to 420 °C. How many ideal stages are needed?

14.3. Suppose the equipment for example 14.1 is built and is working smoothly. Then, one day we are told that the temperature of the incoming solids will be raised to 1,020 °C. We still want the solids to leave at 220 °C, and we don't want to modify the equipment, add stages, etc. What do you suggest we do?

14.4. We wish to heat a stream of solids (1 t/h, $C_p = 1{,}000$ J/kg K) from 0 °C to 800 ° C in a 4-stage direct-contact crossflow fluidized bed exchanger using hot air at 1,000 °C. What is the required volumetric flow rate of air?
Data: For incoming air, $\pi = 120$ kPa, $C_p = 32$ J/mol K.

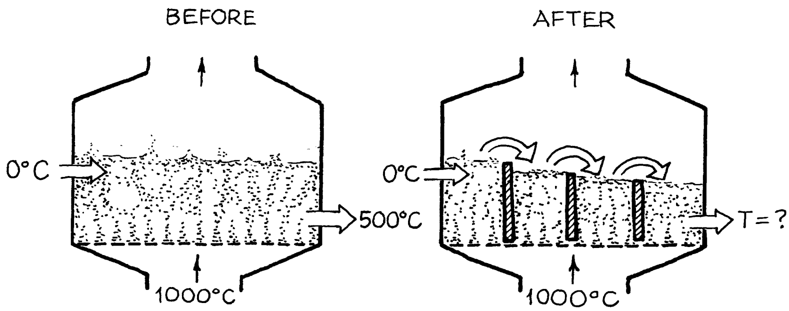
Our factory needed to cool a continuous stream of 880 ° C solids with a stream of 40 ° C air. For this purpose we built a single-stage fluidized bed exchanger as shown in (a), and for the flow rates of our process, we find that the solids leave at 320 °C. This is not bad, but it is not good enough. Let us try to improve the operations.



14.5. One thought is to put a vertical baffle right down the middle of the unit as shown in (b). Keeping all flow rates unchanged, find the temperature of solids leaving the exchanger.

14.6. Another thought is to insert a horizontal baffle in the exchanger, as shown in (c). Again, with flow rates unchanged, find the temperature of the leaving solids.

14.7. At present a stream of hot gas (1,000 °C) contacts a stream of cold solids (0 °C) in a single-stage fluidized bed exchanger. The stream of solids leaves at 500 °C. This is not good enough so let us add baffles so as to divide the exchanger into four equal parts, as shown below, keeping all flows unchanged. With this modification find the temperature of the leaving solids and the leaving gas.



14.8. Hot gas at 1,000 °C enters a three-stage direct-contact crossflow fluidized bed exchanger and contacts a stream of solids which enter at 0 °C. The solids leave at 512 °C. We now add vertical baffles so as to divide each stage into two, thus ending up with six crossflow stages.

(a) By making this change what happens to the temperature of the leaving solids?
(b) How does this change affect the contacting efficiency for the two streams? To answer calculate the contacting efficiency before and after the change.

14.9. Consider a gas–solid direct-contact fluidized bed heat exchanger. If a four-stage crossflow exchanger can heat solids from 20 °C to 820 °C using hot entering gas at 1,020 °C, how many stage counterflows (with the same entering temperatures for gas and solids) can do the same job?

14.10. Consider a gas–solid direct-contact fluidized bed heat exchanger. If a five-stage crossflow exchanger is needed to heat the solids from 0 °C to 600 °C using hot gas at 1,000 °C, how many stage counterflows can do the same job if the inlet gas and solid flow rates and temperatures remain unchanged?

14.11. *Moving bed contactor.* 10 t/h of solids ($C_p = 800$ J/kg K, $T_{s,\text{in}} = 1{,}000$ K) enter the top of a vertical pipe and move down against an upflowing stream of gas ($C_p = 800$ J/kg K, $T_{g,\text{in}} = 500$ K). Plot the temperature distribution of gas and solids in the pipe, and show on the plot the outlet temperature of the two streams.

(a) Gas flow is 10 t/h.
(b) Gas flow is 20 t/h.
(c) Gas flow is 8 t/h.
(d) Find the mean residence time of gas $\bar{t}_g$ and of solids $\bar{t}_s$ in the contactor for the flows of part (a).

Assume perfect countercurrent plug flow contacting, fairly small particles, and a bed voidage $\varepsilon = 0.4$.

14.12. *Moving grate contactor.* Cold crushed solids (small particles, $\dot{m}_s = 10$ kg/s, $C_p = 1{,}000$ J/kg K, $T = 300$ K) are fed to a horizontal moving grate where they are heated by hot upflowing air ($\pi = 116{,}000$ Pa, $T = 600$ K, $v = 12\ \text{m}^3/\text{s}$, $C_p = 36$ J/mol K). Estimate the temperature of the leaving solids and leaving gas for the following extremes:

(a) If the layer of solids on the grate is thick enough so that we can reasonably assume a sharp temperature front in the vertical direction as well as in the horizontal direction.
(b) If the solids on the grate are gently fluidized, hence well mixed in the vertical direction, but not in the horizontal direction.

14.13. Repeat Problem 14.12 with one change—the flow rate of solids is $\dot{m}_s = 15$ kg/s.

14.14. Repeat Problem 14.12 with one change—the flow rate of solids is $\dot{m}_s = 5$ kg/s.

14.15. To improve the efficiency of a shale processing plant, fresh shale is to be preheated by hot waste combustion gases from the process. To do this, a layer of finely crushed fresh shale rock (0 °C) is transported along a long horizontal porous conveyor belt while the hot gas (640 °C) is forced upward through the bed at a high enough velocity to just fluidize the solids.

At present the shale leaves at 480 °C. What would be the outlet temperature of the solids if the gas flow rate were:

(a) Raised 20 %?
(b) Lowered 20 %, in which case the fluidized bed collapses into a moving fixed bed of solids?

Related Reading

D. Kunii, O. Levenspiel, *Fluidization Engineering*, 2nd edn. (Butterworth, Boston, 1991)