THE LATERAL EFFECTIVE THERMAL CONDUCTIVITY IN A PACKED FLUIDIZED BED

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Several kinds of particles were fluidized with air in columns packed with open-end cylindrical screen packing and the lateral effective thermal conductivity was measured in the bed. The effective thermal conductivity in a packed fluidized bed was affected by the packing size, the minimum fluidization gas velocity, properties of fluidized particles, the void fraction of packing and the intensity of fluidization. The empirical equation for the lateral effective thermal conductivity for a packed fluidized bed was obtained.

Introduction

The effective thermal conductivity in a packed fluidized bed is an important factor in the design of a packed fluidized bed in many fields such as the regeneration of activated carbon, the drying of particles, a catalytic reaction, a gas-solid reaction, and so on. Since the effective thermal conductivity in a packed fluidized bed is strongly affected by the solid mixing in the bed, the intensity of solid mixing can be approximately estimated from that value. A radial or a lateral effective thermal conductivity in a packed fluidized bed with spherical packing has been investigated by Ziegler *et al.*⁽³⁾, Gabor⁽¹⁾, and Hirama *et al.*⁽²⁾. Lattice-type packings or cylindrical screen packings are more favorable for a solid-gas catalytic reaction or drying of particles because of the large void fraction of these packings. However, the lateral effective thermal conductivity for these cases has not been investigated yet.

In this paper the lateral effective thermal conductivity is investigated in a packed fluidized bed with open-end cylindrical screen packing. The lateral effective thermal conductivity was affected by the packing size, properties of fluidized particles, U/U_{mf} , and the void fraction of packings. An empirical equation for the lateral effective thermal conductivity in a packed fluidized bed was obtained.

1. Experimental Apparatus and Procedure

A schematic diagram of experimental apparatus is shown in Fig. 1. A rectangular column made of acrylic resin was used. Its dimensions were 20 cm

width, 8 cm thickness and 30 cm length. A perforated plate of 3 mm thickness and 1 mm pore size was used as the gas distributor.

To measure the lateral temperature distribution a plain source, 7 cm × 20 cm, in which an electrical resistance coil was enclosed was placed on one side of the bed. On the other side, the cooling part, 7 cm × 20 cm, was placed. Cooling water was circulated to the cooling part, its temperature controlled by an electric cooler. To measure the temperature distribution across the bed, six copper-constantan thermocouples were usually placed in the bed as shown in Fig. 1. Sometimes other thermocouples were placed in suitable places in the bed. To fix the point of temperature measurement, these thermocouples were inserted into very small glass tubes of 2.0 mm I. D.

Fig. 1 Experimental apparatus

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Table 1 Packings used in this experiment

	Sign	$d \times 10^2$ [m]	$h \times 10^2$ [m]	$D_p^* \times 10^2$ [m]	ε_p [—]
Cylindrical wire net	PN-1	1.15	1.09	1.29	0.960
	PN-2	2.60	2.60	3.01	0.990
	PN-5	1.80	1.80	2.07	0.975
	PN-7	2.73	4.22	3.61	0.990
	PN-9	2.00	2.54	2.48	0.990
Glass spheres	PG-1			1.31	0.410
	PG-2			2.45	0.460

Table 2 Fluidized particles used in this experiment

	Diameter [mesh]	U_{mf} [m/hr]	C_{ps} [kcal/kg·°C]	ρ_s [kg/m ³]
Glass beads	— 35 + 65	468	0.18	2.5×10^3
	— 42 + 60	324		
	— 80 + 100	86		
	— 170 + 250	32		
Activated alumina	— 60 + 80	252	0.23	3.5×10^3
	— 80 + 150	115		
	— 150 + 250	79		
Zircon sand	— 60 + 115	137	0.15	4.5×10^3
Silica sand	— 48 + 115	173	0.235	2.7×10^3

These tubes were placed in the bed horizontally and perpendicularly to the direction of heat flow. At the point of temperature measurement the thermocouples were exposed to the bed. The electric potential differences of these thermocouples were measured by microvoltmeter and recorded by X-Y recorder. The column was covered with lagging material to minimize heat loss from the bed.

Packings used in this experiment are shown in **Table 1**. In this paper the size of packing is expressed by the sign shown in Table 1. D_p^* in Table 1 is the equivalent diameter of packing defined as $\{(3/2)d^2h\}^{1/3}$. Properties of fluidized particles used in this experiment are shown in **Table 2**.

When the bed reached thermal equilibrium, the lateral effective thermal conductivity ke in a packed fluidized bed was calculated from Fourier's equation by measuring the heat flow rate in the lateral direction Q_{le} , the temperature gradient in the bed $\Delta T/\Delta L$, and heat transfer area A .

$$Q_{le} = -ke \cdot A \cdot \Delta T/\Delta L \quad (1)$$

2. Experimental Results

To investigate the lateral effective thermal conductivity accurately, the axial temperature distribution must be uniform. **Figure 2** shows the axial temperature distribution at 5 cm from the heat source. From Fig. 2 the axial temperature difference was less than 0.7°C. Temperature difference of the lengthwise direction was also less than 0.3°C except near the bed wall. **Figure 3** shows the lateral temperature distribution in the case where 42–60 mesh glass beads are fluidized among PN-5 packings. In this experiment, temperatures at the surface of heat

Fig. 2 Relationship between T and Z

Fig. 3 Relationship between T and L

source and cooling part were 65–50°C and 14–6°C, respectively. From Fig. 3 the lateral temperature distribution becomes a straight line except near the heat source and near the cooling part. The value of $\Delta T/\Delta L$ is nearly constant under certain operating conditions.

Figure 4 shows the relationship between the effective thermal conductivity ke and the superficial gas velocity U with the minimum fluidized gas velocity as a parameter in the case where glass beads are fluidized among PN-9 packings. From Fig. 4 the effective thermal conductivity increases with increase of superficial gas velocity at constant fluidized particle size and increases with decrease of particle size at constant superficial gas velocity. These facts mean that the mixing of particles increases with increase of superficial gas velocity and becomes vigorous in the case of small particles at constant superficial gas velocity.

Fig. 4 Relationship between ke and U

Fig. 5 Relationship between ke and U

Fig. 6 Relationship between ke and $(U - U_{mf})/U_{mf}$

This tendency was observed in other fluidized systems.

Figure 5 shows the relationship between effective thermal conductivity ke and U with packing size as a parameter when 80-100 mesh glass beads and 150-200 mesh activated alumina particles are fluidized among the packings, respectively. As shown in Fig. 5, ke increases with increase of D_p^* at constant gas velocity. That is, the particles are fluidized vigorously

Fig. 7 Relationship between ke and $(U - U_{mf})/U_{mf}$

Fig. 8 Relationship between ke and D_p^*

Fig. 9 Relationship between ke and U_{mf}

in the bed with large packing. A similar tendency was shown in other fluidized systems.

Now the lateral effective thermal conductivity in a packed fluidized bed may be affected by the packing size D_p^* , the property of fluidized particles U_{mf} , C_{ps} , ρ_{bmf} , the intensity of fluidization $(U - U_{mf})/U_{mf}$, and so on.

Figure 6 shows the relationship between the effective thermal conductivity ke and $(U - U_{mf})/U_{mf}$ with

Fig. 10 Relationship between ke and $(U - U_{mf})/U_{mf}$

minimum fluidized gas velocity U_{mf} as a parameter when glass beads are fluidized among PN-9 packings. From Fig. 6 ke increases with increase of particle size at constant value of $(U - U_{mf})/U_{mf}$.

The relationship between ke and $(U - U_{mf})/U_{mf}$ is shown in Fig. 7 with equivalent diameter of packing D_p^* as a parameter in the case where 80–100 mesh glass beads are fluidized. Figure 7 indicates that the lateral effective thermal conductivity ke becomes large in the case of large packing at constant value of $(U - U_{mf})/U_{mf}$. From Figs. 6 and 7 ke is proportional to $(U - U_{mf})/U_{mf}$ at constant fluidized particle size and constant packing size.

To examine the effect of packing size on effective thermal conductivity, Figure 8 shows the relationship between ke at $(U - U_{mf})/U_{mf} = 5$ and D_p^* with minimum fluidized gas velocity U_{mf} as a parameter. From Fig. 8, ke is proportional to $D_p^{*1.4}$.

Figure 9 shows the relationship between ke at $(U - U_{mf})/U_{mf} = 5$ and U_{mf} with packing size D_p^* as a parameter. As shown in Fig. 9, ke is approximately proportional to $U_{mf}^{0.7}$.

To investigate the effect of fluidized particle properties on the lateral effective thermal conductivity, the thermal conductivity of glass beads, activated alumina particles, zircon sand particles and silica sand particles was investigated under almost constant values of U_{mf} , U/U_{mf} and packing size. From these investigations ke was approximately proportional to $(C_{ps}/\rho_{bmf})^{1/3}$.

To investigate the effect of packing shape on effective thermal conductivity, Fig. 10 shows the relationship

Fig. 11 Relationship between $ke/D_p^{*1.4} \cdot U_{mf}^{0.7} \cdot (C_{ps}/\rho_{bmf})^{1/3} \cdot \epsilon_p$ and $(U - U_{mf})/U_{mf}$

between ke and $(U - U_{mf})/U_{mf}$ in the case where 42–60 mesh glass beads are fluidized among spherical packings (PG-1) and among screen packings (PN-1). Figure 10 indicates that ke is large in the case of screen packings at constant size of packing. From Fig. 10 ke is proportional to the fraction of packings ϵ_p . Furthermore, Fig. 10 shows the effective thermal conductivity in an ordinary fluidized bed for this apparatus. ke in an ordinary fluidized bed may be strongly affected by bed diameter and bed height. It cannot be simply compared with ke in a packed fluidized bed, but ke in an ordinary fluidized bed is about 10 times larger than that in a packed fluidized bed under these experimental conditions.

Figure 11 shows the relationship between $ke/(D_p^{*1.4} \cdot U_{mf}^{0.7} \cdot (C_{ps}/\rho_{bmf})^{1/3} \cdot \epsilon_p)$ and $(U - U_{mf})/U_{mf}$. This relationship correlates well not only with these present data in the case of screen packing, but also with the data of Ziegler *et al.*³⁾, Gabor¹⁾, and HIRAMA *et al.*²⁾ in the case of spherical packing. From Fig. 11, the following empirical equation for the lateral effective thermal conductivity in a packed fluidized bed is obtained:

$$ke = 2.72 \times 10^3 \cdot D_p^{*1.4} \cdot U_{mf}^{0.7} \cdot (C_{ps}/\rho_{bmf})^{1/3} \cdot \epsilon_p \cdot (U - U_{mf})/U_{mf} \quad (2)$$

In Eq. (2), the units of ke , D_p^* , U_{mf} , C_{ps} , ρ_{bmf} , ϵ_p , U are [kcal/m·hr·°C], [m], [m/hr], [kcal/kg·°C], [kg/m³], [—], [m/hr], respectively. Equation (2) is applicable when the packing size is 0.01–0.04 [m], U_{mf} is 30–1700 [m/hr], C_{ps}/ρ_{bmf} is 2.0×10^{-5} – 1.6×10^{-4} [kcal·m³/kg²·°C], ϵ_p is 0.4–0.99 [—] and U/U_{mf} is 1.2–40 [—].

3. Discussion

In this experiment, the following heat losses are considered: that from the bed wall and that by sensible heat of fluidized gas. To minimize those heat losses, the bed temperature was adjusted to be almost room temperature. From a rough calculation, heat loss from the bed wall was less than 2% of total heat supplied and may be negligible. The heat loss by the sensible heat of fluidized gas was less than 17% of the total heat supplied. Since the sensible heat of fluidized gas transfers from the upper and lower surfaces of the bed in different heat fluxes, this heat loss does not directly affect the value of ke , and its effect upon ke will be small.

In addition to those heat losses, the experimental error in measurement of heat transfer area is also considered. This error becomes large in the case of vigorous fluidized conditions with large packing size. But this error was also less than several percent in a packed fluidized bed.

There are three possible ways by which heat can be transferred laterally in a packed fluidized bed: conductive heat transfer due to the flowing gas, conduction through the packing, and conductive heat transfer due to the mixing of fluidized particles. In these experimental results the mixing of fluidized particles is the main factor for the lateral effective thermal conductivity in a packed fluidized bed. That is, the movement (mixing) of fluidized particles increases with increase of superficial gas velocity and ke is proportional to $(U - U_{mf})/U_{mf}$ in Eq. (2).

Under constant superficial gas velocity, the smaller the size of fluidized particles and the lower the density of fluidized particles are, the more easily the particles are apt to be fluidized. Therefore, the lateral effective thermal conductivity is inversely proportional to $U_{mf}^{0.3}$ and $\rho_{bmf}^{1/3}$ in Eq. (2). On the other hand, the movement of fluidized particles becomes vigorous in the case of large packings at constant superficial gas velocity and ke is proportional to $D_p^{*1.4}$ in Eq. (2). This fact can also be shown in Fig. 10. There is a

large difference between ke for a packed fluidized bed and that for an ordinary fluidized bed obtained by this experimental apparatus. The movement of fluidized particles becomes vigorous in the case of a large void fraction of packings at constant packing size and ke is proportional to ε_p in Eq. (2).

Conclusion

The lateral effective thermal conductivity ke in a packed fluidized bed is affected by the packing size, the minimum fluidized gas velocity, properties of fluidized particles, the intensity of fluidization and the void fraction of packing. ke is calculated from Eq. (2) within the ranges from 1.0×10^{-2} to 4.0×10^{-2} [m] in D_p^* , 30 to 1700 [m/hr] in U_{mf} , 1.2 to 40 [—] in U/U_{mf} , 2.0×10^{-5} to 1.6×10^{-4} [kcal·m³/kg²·°C] in (C_{ps}/ρ_{bmf}) and 0.4 to 0.99 [—] in ε_p .

Nomenclature

A	= heat transfer area	[m ²]
C_{ps}	= heat capacity of fluidized particles	[kcal/kg·°C]
D_p^*	= equivalent diameter of packing defined as $(3/2d^2h)^{1/3}$	[m]
d	= diameter of screen packing	[m]
h	= length of screen packing	[m]
ke	= lateral effective thermal conductivity	[kcal/m·hr·°C]
L	= distance from heater	[m]
Q_{te}	= heat flow rate in the lateral direction	[kcal/hr]
T	= bed temperature	[°C]
U	= superficial gas velocity	[m/hr]
U_{mf}	= the minimum fluidized gas velocity	[m/hr]
Z	= axial length from distributor	[m]
ρ_s	= density of particles	[kg/m ³]
ρ_{bmf}	= bulk density of fluidized particle at the minimum fluidized condition	[kg/m ³]
ε_p	= void fraction of fixed packing	[—]

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