HEAT TRANSFER OF PARTICLES IN PNEUMATIC ESCALATOR

KUNIO SHINOHARA AND ATSUSHI YASUDA
*Department of Chemical Process Engineering,
Hokkaido University, Sapporo 060*

Pneumatic escalator is examined as to its heat transfer characteristics with particles. Change in particle temperature in the horizontal direction of overall particle flow is measured by a radiation thermometer. An experimental equation of particle temperature is made under various operating conditions such as air flow rate, particle feed rate and inlet air temperature. An apparent coefficient of heat transfer based on particle temperature alone is evaluated by heat balance and rate of heat transfer between particles and air or wall surfaces.

As a result, it is found that Nusselt's number increases with particle Reynolds number, particle concentration and average temperature of air within each sectionalized cell and with decreasing particle size. Thus, a pneumatic escalator could suitably be designed and utilized for continuous and simultaneous heating operations on the basis of the heat transfer data obtained.

Introduction

A pneumatic escalator was devised for transporting powder upwards with air⁽⁴⁾, within which the residence time distribution of particles is adjustable to a large extent⁽⁵⁾. Thus the present device could also be used for simultaneous operation of solids-gas contact in continuous processes.

Heat transfer is investigated here in close relation to such operations as preheating or cooling, drying and thermal decomposition of particulate materials. Several coefficients of heat transfer inherent in the device can be defined and compared under several operating conditions. The coefficient evaluated by measuring particle surface temperature is finally chosen. It results in a smaller value than other coefficients based on temperatures of blowing air and particle assembly involving heated air voids.

Experimental results are resolved by computation and expressed by a dimensionless equation of heat transfer analogous to that of forced convection for a single particle. The equation includes effects of conduction and radiation between particles and wall surface of the device as well. Temperature distributions of air and solids are to be described, and thus the pneumatic escalator can be suitably designed and operated for various purposes.

1. Equipment and Procedure

Figure 1 shows the experimental equipment. It consists of a pneumatic escalator, hoppers with an

orifice, an electric heater to which air is conducted from a blower, and thermocouples and a radiation thermometer connected with recorders. Firstly, when the system attained steady state without particles at total flow rate of air at room temperature, Q_{ri} , and a certain preset temperature in the air box just below the filter, the thermocouple inserted closely above each sectionalized cell indicated temperature distribution of inlet air, $T_{ai,n}$. Secondly, particles were supplied at the right end of the device through the orifice at constant feed rate, F . Particles are blown up along inclined plates and conveyed to the next cell with heated air. After outlet air temperature, $T_{ao,n}$, became constant, air and particle supply were simultaneously stopped and particle surface temperature in each

Fig. 1 Experimental equipment

Received May 2, 1977. Correspondence concerning this article should be addressed to K. Shinohara,

Table 1 Physical properties of particle and air, dimensions of pneumatic escalator, and range of operating conditions

Glass beads	$d_p = 119, 358, 1023 \text{ } [\mu\text{m}]$, $\rho_p = 2520 \text{ } [\text{kg}/\text{m}^3]$, $C_p = 0.18 \text{ } [\text{kcal}/\text{kg}/^\circ\text{C}]$
Air	$C_a^{(1)} = \{6.27 \pm 2.09 \times 10^{-8}$ $\times (T_{av} + 273.2) - 0.459$ $\times 10^{-6} \times (T_{av} + 273.2)^2\}$ $/28.97 \text{ } [\text{kcal}/\text{kg}/^\circ\text{C}]$ $\rho_a^{(3)} = 353.2/(273.2 + T_{av}) \text{ } [\text{kg}/\text{m}^3]$ $\mu_a^{(2)} = 0.005411 \times (T_{av} + 273.2)^{1.5}$ $/(T_{av} + 396.8) \text{ } [\text{kg}/\text{m}/\text{hr}]$
Pneumatic Escalator	$l = 6.27 \times 10^{-2} \text{ } [\text{m}]$, $b = 6.00 \times 10^{-3} \text{ } [\text{m}]$, $D = 2.00 \times 10^{-2} \text{ } [\text{m}]$, $\theta_p = 53.0 \text{ } [^\circ]$, $W = 2.01 \times 10^{-2} \text{ } [\text{m}]$, $N = 18 \text{ } [-]$
Operational conditions	$7.90 \leq Q_r \text{ } [\text{m}^3/\text{hr}] \leq 65.9$ $1.757 \leq F \text{ } [\text{kg}/\text{hr}] \leq 47.0$ $151.0 \leq T_{ai} \text{ } [^\circ\text{C}] \leq 367.0$

cell, $T_{p,n}$, was quickly measured with a radiation thermometer. Total holdup, H , within the device was also weighed to confirm the dimensionless equation of particle transportation mentioned later.

Glass beads were used as particles. Their material properties are listed in **Table 1**. Three particle sizes were prepared, to expand the range of Reynolds' Number. Effects of operating conditions like Q_{rt} , F and T_{ai} on heat transfer with the pneumatic escalator primarily were examined.

Before the above-mentioned experiment the thermometer was calibrated by comparing the temperature of natural glass beads with emissivity of nearly unity with that of painted beads. Particles were spread evenly on a disk to be separated diametrically into two parts, one of which was sprayed with black paint of emissivity 0.97. Then both parts were heated uniformly by electrical means. The two kinds of glass beads should therefore be at the same temperature, that is, the temperature of black painted beads and that of natural beads of unity emissivity. **Figure 2** depicts calibration curves for three bead diameters, where distance between camera and particle surface was confirmed to ensure uniformity in temperature under almost the same conditions as with the pneumatic escalator. The angle of the beam to the horizontal particle surface was 53° , corresponding to the inclination angle of the parallel plates of the sectionalized cell.

2. Fundamental Consideration

To appraise heat transfer characteristics with the present device, thermal data were analyzed from the viewpoint of heat transfer coefficient as usual.

Heat balance between particles and air can briefly be written by Eqs. (1), (2) and (3) under the following assumptions:

1) Within each cell, particles are completely mixed

Fig. 2 Calibration curves of particle temperature

at random with fluidizing air and there is thus no particle-temperature distribution superficially along vertical sides and sectionalizing plates.

II) Wall temperature is close to air temperature at each point of sides and plates, because the cells section is covered with adiabatic woolly material so sufficiently that air and wall temperatures should be in equilibrium without serious heat loss.

III) Thermocouples closely above the cells detect well the approximate inlet air temperature without particle feed. Equations (1) and (2) represent heat gained by particles and heat loss of air, respectively, at the n -th cell in the device.

$$q_n = F \cdot C_p \cdot (T_{p,n} - T_{p,n-1}) \quad (1)$$

$$q_n = Q_n \cdot \rho_a \cdot C_a \cdot (T_{ai,n} - T_{ao,n}) \quad (2)$$

where subscripts a and p indicate air and particle, and i and o mean inlet and outlet, respectively. Equation (3) expresses overall rate of heat transfer between particles and air or wall at the n -th cell.

$$q_n = h_n \cdot S_w \cdot H_n \cdot \Delta T_{lm,n} \quad (3)$$

where h_n is apparent coefficient of heat transfer inherent in the present device. Assuming nearly constant coefficient within each cell, logarithmic mean temperature difference, $\Delta T_{lm,n}$, between average temperature of particles and those of inlet and outlet air can be applied.

$$\Delta T_{lm,n} = \frac{T_{ai,n} - T_{ao,n}}{\log_e \{ (T_{ai,n} - T_{p,n}) / (T_{ao,n} - T_{p,n}) \}} \quad (4)$$

Here, effective or representative area for heat transfer is considered to be the total area of particles surface. It is given by multiplying holdup in each cell, H_n , by specific surface of particles on weight basis, S_w , because the particles are supposed to be well mixed and circulated at random, as mentioned before.

Apparent coefficient of heat transfer, h_n , is, therefore, derived from the above equations as follows:

Fig. 3 Variation of air and particle temperature along sectionalized cells in pneumatic escalator

Fig. 4 Comparison among three kinds of coefficients of heat transfer

When particle temperature $T_{p,n}$ as well as outlet air temperature $T_{ao,n}$ in each cell can accurately be measured, Eqs. (2) and (3) give $h_{ap,n}$ in general as

$$h_{ap,n} = \frac{Q_n \cdot \rho_a \cdot C_a}{S_w \cdot H_n} \cdot \log_e \frac{T_{ai,n} - T_{p,n}}{T_{ao,n} - T_{p,n}} \quad (5)$$

But, when only air temperature can be measured, equating Eqs. (1) and (2) gives particle temperature as a function of air temperature by

$$T_{p,n} = T_{p,f} + \frac{1}{F \cdot C_p} \cdot \sum_{n=1}^n (T_{ai,n} - T_{ao,n}) \cdot Q_n \cdot \rho_a \cdot C_a \quad (6)$$

Thus, substitution of Eq. (6) into Eq. (5) leads to $h_{a,n}$ excluding $T_{p,n}$ as

$$h_{a,n} = \frac{Q_n \cdot \rho_a \cdot C_a}{S_w \cdot H_n} \cdot \log_e \left[\left\{ T_{ai,n} - T_{p,f} - \frac{1}{F \cdot C_p} \sum_{n=1}^n (T_{ai,n} - T_{ao,n}) \cdot Q_n \cdot \rho_a \cdot C_a \right\} / \left\{ T_{ao,n} - T_{p,f} - \frac{1}{F \cdot C_p} \sum_{n=1}^n (T_{ai,n} - T_{ao,n}) \cdot Q_n \cdot \rho_a \cdot C_a \right\} \right] \quad (7)$$

When measurement of particle temperature is more precise than that of outlet air, $h_{p,n}$ is also obtained as Eq. (8) from particle temperature alone by putting Eq. (9) into Eq. (5).

$$h_{p,n} = - \frac{Q_n \cdot \rho_a \cdot C_a}{S_w \cdot H_n} \cdot \log_e \left(1 - \frac{F \cdot C_p}{Q_n \cdot \rho_a \cdot C_a} \cdot \frac{T_{p,n} - T_{p,n-1}}{T_{ai,n} - T_{p,n}} \right) \quad (8)$$

$$T_{ao,n} = T_{ai,n} - \frac{F \cdot C_p}{Q_n \cdot \rho_a \cdot C_a} (T_{p,n} - T_{p,n-1}) \quad (9)$$

where Eq. (9) is another expression of Eq. (6) with respect to $T_{ao,n}$. Then arithmetic mean temperature of inlet and outlet air in each cell, $T_{av,n}$, is written by using Eq. (9) as

$$T_{av,n} = \frac{T_{ai,n} + T_{ao,n}}{2} = T_{ai,n} - \frac{F \cdot C_p}{2 \cdot Q_n \cdot \rho_a \cdot C_a} (T_{p,n} - T_{p,n-1}) \quad (10)$$

As a measure of h_n in design, if distributions of inlet air temperature and heat transfer coefficient can be regarded as uniform throughout the device, Eq. (5) is rewritten with respect to $T_{p,n}$ as Eq. (11).

$$T_{p,n} = \frac{T_{p,f}}{(1+K)^n} + \left\{ 1 - \frac{1}{(1+K)^n} \right\} \cdot T_{ai} \quad (11)$$

where both Q_n and H_n could be constant throughout the cells at constant temperature of inlet air for reference, and

$$K = \frac{Q_n \cdot \rho_a \cdot C_a}{F \cdot C_p} (1 - e^{-(S_w \cdot H_n / Q_n \cdot \rho_a \cdot C_a) \cdot h_{pv,n}}) \quad (12)$$

Hence, average coefficient of heat transfer, $h_{pv,n}$, is expressed by rewriting Eq. (11) further as Eq. (13).

$$h_{pv,n} = - \frac{Q_n \cdot \rho_a \cdot C_a}{S_w \cdot H_n} \cdot \log_e \left[\left(1 - \frac{F \cdot C_p}{Q_n \cdot \rho_a \cdot C_a} \cdot \left\{ \left(\frac{T_{ai} - T_{p,f}}{T_{ai} - T_{p,n}} \right)^{1/n} - 1 \right\} \right) \right] \quad (13)$$

Equation (13) indicates that only one point measurement of particle temperature gives the average coefficient of heat transfer for the pneumatic escalator under certain operating conditions.

3. Results and Discussion

Experimental data in Fig. 3 illustrate that inlet air temperature is a bit lower at both ends of the device, and that temperatures of outlet air and particle increase with the number of the cell or distance from the feed point. Calculated lines are depicted for comparison by Eq. (9) and an experimental equation of particle temperature, Eq. (14), mentioned later. The line of $T_{p,n}$ well describes the data, but the line of $T_{ao,n}$ comes far above the data.

In the present device, thermocouples are horizontally inserted 10 mm above the cells and on the central plane parallel to sectionalizing plates, as shown in

Fig. 1. Hence, outlet air temperature is doubtful or possibly lower than the true value due to collision of flying particles with the sensing end of the thermocouple.

Figure 4 shows variation of h_n along overall path of particle flow based on three kinds of estimation from Eqs. (5), (8) and (13) for reference. It is easily understood by Eq. (5) that $h_{ap,n}$ usually becomes large for $T_{ao,n}$ lower or $T_{p,n}$ higher than the true temperature. In addition h_n should be essentially independent of particle temperature or the number of the cell without serious radiative effect, and thus no striking change as in $h_{ap,n}$ would be observed. As a consequence, $h_{p,n}$ by Eq. (8) is adopted here as a calculated value by measuring only particle surface temperature, $T_{p,n}$, with the radiation thermometer.

Since the so-called dimensionless numbers of Nusselt and Reynolds both include factors dependent on air temperature, they change with n and, strictly speaking, within each cell under the same operating condition even for constant h_n throughout the present device. The following steps were, therefore, taken to describe its heat transfer characteristics. Firstly, measured values of $T_{p,n}$ were plotted directly against total volumetric flow rate of air at room temperature, Q_{rt} , particle feed rate, F , inlet air temperature, $T_{ai,n}$, and the number of the cell, n . The experimental equation was obtained as Eq. (14) and its correlation with data is shown in **Fig. 5**.

$$\begin{aligned} T_{p,n} &= T_{p,f} + (T_{ai,n} - T_{p,f})(1 - ce^{-an}) \quad (14) \\ a &= 0.064 \cdot Q_{rt}^{0.90} \cdot F^{-0.86} \cdot \exp(-1080 \cdot d_p) \\ c &= 0.050 \cdot T_{ai}^{0.23} \cdot Q_{rt}^{0.12} \cdot d_p^{-0.16} \end{aligned}$$

where power of T_{ai} is determined at first in the range $6 \leq n \leq 14$ for nearly constant T_{ai} . Equation (14) was used for analysis in place of the data of $T_{p,n}$ corresponding to arbitrary operating conditions within the experimental range.

In order to appreciate numerical values of $h_{p,n}$ obtained with the pneumatic escalator, original thermal data were converted through Eqs. (14) and (18) into dimensionless numbers including voidage, ϵ , within each cell after the analogy of heat transfer data of a single sphere as

$$\frac{h_p \cdot d_p}{k_a} = f\left(\frac{d_p \cdot U_{vd} \cdot \rho_a}{\mu_a}, \epsilon, \frac{T_{av}}{T_{p,f}}, \frac{d_p}{D}\right) \quad (15)$$

where U_{vd} is not superficial velocity of air but linear velocity through voids among particles. Besides flow rate of air, physical properties like viscosity, μ_a , specific heat, C_a , density, ρ_a , and thermal conductivity, k_a , are all dependent on air temperature. Thus, $T_{av,n}$ can be used to estimate the properties approximately. The Prandtl number of air is nearly constant above 100°C, so that it is omitted in Eq. (15). Assuming uniform dispersion of particles within each cell,

Fig. 5 Correlation of experimental equation with data of particle surface temperature

Fig. 6 Confirmation of dimensionless equation for particle transportation

voidage, ϵ_n , and air velocity, $U_{vd,n}$, gives holdup, H_n , and air flow rate, Q_n , in the n -th cell, respectively, as

$$H_n = l \cdot D \cdot W \cdot \rho_p \cdot (1 - \epsilon_n) \quad (16)$$

$$Q_n = U_{vd,n} \cdot \epsilon_n \cdot D \cdot W \quad (17)$$

Holdup is related to particle feed rate, F , as well as Q_{rt} and $T_{av,n}$ by our previous equation for particle transportation⁵⁾. For higher precision three equations are prepared for three particle sizes.

$$d_p = 119 \mu\text{m}: F = 2.04 \times 10^7 \cdot H_n^{4.93} \cdot Q_{rt}^{4.26} \cdot \mu_a^{2.17} \cdot \rho_a^{-0.18} \quad (18)$$

$$d_p = 358 \mu\text{m}: F = 1.52 \times 10^8 \cdot H_n^{5.41} \cdot Q_{rt}^{3.77} \cdot \mu_a^{2.38} \cdot \rho_a^{-0.30} \quad (19)$$

$$d_p = 1023 \mu\text{m}: F = 20.5 \cdot H_n^{6.41} \cdot Q_{rt}^{8.21} \cdot \mu_a^{2.82} \cdot \rho_a^{-0.54} \quad (20)$$

Figure 6 confirms Eqs. (18)–(20) under present operating conditions. Hence, keeping T_{ai} , T_{av} and ϵ constant and changing U_{vd} for one d_p gives Nu vs. Re by using Eqs. (8) and (14)–(20) to evaluate the power of Reynolds Number, as shown in **Fig. 7**. By a plotting method similar to that used for **Fig. 8**, other dimensionless terms become definite as Eq. (21)

Fig. 7 Nu vs. Re plots

Fig. 8 Effect of average air temperature on heat transfer

$$Nu = 1.52 \times 10^{-4} \cdot Re^{1.72} \cdot (1 - \epsilon)^{-0.51} \times \left(\frac{T_{av}}{T_{p,f}} \right)^{0.25} \cdot \exp \left(-46.7 \frac{d_p}{D} \right) \quad (21)$$

Figure 9 shows the final correlation between all the data and computed results by Eq. (21).

According to definition of heat transfer coefficient by Eq. (3), h_p involves not only the effect of convection but also those of heat conduction and radiation through air film among wall and particle surfaces. But, because of complicated behavior of particles within each cell their effects were difficult to estimate separately by experiment.

Previous experiments with fluidized beds might be accompanied by heat loss or might detect interparticle temperature as T_p , which involves air temperature, by inserting a thermocouple into the particle bed. In

Fig. 9 Final correlation of heat transfer data with pneumatic escalator

such a case, lower T_{ao} or higher T_p should be measured than true temperature, so that h_{ap} becomes large superficially, as mentioned before. The term $(1 - \epsilon)$ of Eq. (21) could be regarded as the effect of particle concentration on convective heat transfer with one sphere and is governed by particle feed rate as well as air flow rate. It would be quite natural that Eq. (21) for particle cloud usually comes below Ranz-Marshall's equation³⁾. Concerning the temperature term, radiation might be effective in contrast with the nearly constant Prandtl number of air in this experiment. The particle size term would relate closely to degree of dispersion and mixing of particles within each cell at the same particle concentration. Smaller particles seemed to disperse more uniformly and to be better mixed at random by observation, resulting in higher effects of heat convection and radiation.

Conclusions

Heat transfer characteristics in the pneumatic escalator were investigated and the following was learned.

In the present device particle and outlet-air temperature rises along the apparent horizontal path of particle flow, where temperature distribution of inlet air is nearly uniform.

Outlet-air temperature indicated a lower value than the true one, where larger coefficient of heat transfer is obtained from definition. Instead, particle surface temperature is more reliable for estimating heat transfer coefficient which involves contributions of convection, conduction and radiation.

Effects of operating variables such as particle feed

rate, air flow rate and inlet-air temperature on heat transfer are described in the form of a dimensionless equation analogous to that of a single particle by interpolating particle temperature based on the experimental equation. Effects of particle concentration and average air temperature within a cell and particle size on convective heat transfer are also put into the dimensionless equation, which indicates difference from Nu for a single particle. Thermal data from the present device by measurement of particle temperature alone will come below Ranz-Marshall's.

Consequently, the pneumatic escalator could satisfactorily be utilized for simultaneous heat transfer and particle conveying in a continuous dry system.

Acknowledgments

Authors wish to express cordial thanks to Messrs. Yamada, Suhara, Kanemoto and Shinzaki for their great contribution to experiments.

Nomenclature

a	= coefficient in Eq. (14)	
b	= thickness of parallel inclined plate	[m]
C	= specific heat	[kcal/kg/°C]
c	= dimensionless coefficient in Eq. (14)	[—]
D	= distance between parallel inclined plates	[m]
d_p	= diameter of particle	[m]
e	= exponent or base of natural logarithm	[—]
F	= feed rate of particle	[kg/hr]
g	= acceleration due to gravity	[m/hr ²]
H	= holdup of particles within pneumatic escalator	[kg]
h	= apparent coefficient of heat transfer	[kcal/m ² /hr/°C]
k	= thermal conductivity	[kcal/m/hr/°C]
l	= length of parallel inclined plate	[m]
N	= total number of cells of pneumatic escalator	[—]
Nu	= Nusselt number based on particle size	[—]
n	= number of each cell from feed point of particles	[—]

Q	= volumetric flow rate of air through each cell	[m ³ /hr]
Q_{rt}	= total volumetric flow rate of air through filter at room temperature	[m ³ /hr]
q	= heat flow	[kcal/hr]
Re	= Reynolds number based on particle size	[—]
S_w	= specific surface area of particles on weight basis	[m ² /kg]
T	= temperature	[°C]
U_{vd}	= air velocity through voids among particles	[m/hr]
W	= distance between parallel vertical sides	[m]
ε	= void fraction of particles within a cell	[—]
θ_p	= angle of inclined plate against filter	[°]
μ	= viscosity	[kg/m/hr]
ρ	= density	[kg/m ³]

<Subscripts>

a	= air
f	= feed point
i	= inlet of cell
n	= number of cell from feed point of particles
o	= outlet of cell
p	= particle
v	= average

Literature Cited

- 1) "Kagaku Kogaku Binran", p. 54, Maruzen Pub. Co. Ltd., Tokyo (1958).
- 2) *ibid.*, p. 34 (1958).
- 3) Ranz, W. E. and W. R. Marshall, Jr.: *Chem. Eng. Progr.*, **48**, 141 (1952).
- 4) Shinohara, K. and T. Tanaka: *J. Chem. Eng. Japan*, **5**, 279 (1972).
- 5) Shinohara, K., K. Hayashi and T. Tanaka: *ibid.*, **6**, 447 (1973).
- 6) "Yuso Kogaku Handbook", p. 6, Asakura Pub. Co. Ltd., Tokyo (1966).

(Presented at the 11th Autumn Meeting of The Soc. of Chem. Engrs., Japan, October 7, 1977)