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Heat transfer in a particle curtain falling through a horizontally-flowing gas stream

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ABSTRACT

A study of heat transfer between horizontally-flowing air and a free-falling particle curtain was reported. A steady and uniformly distributed stream of cold particles was fed through a rectangular slit and allowed to fall to form a curtain across the entire width of a horizontal duct of cross-section of 0.15×0.60 m. Warm air, at velocities in the range of 0.9 m/s to 1.2 m/s and with a uniform velocity profile, flowed horizontally through the duct. A range of curtain thickness (4 cm to 10 cm) and mass flow rate (0.031 kg/s to 0.040 kg/s) were used to investigate the heat transfer characteristic of the free-falling particle curtain in a uniform cross-flowing gas. Particle temperatures within the curtain and air temperatures outside the curtain were measured as a function of vertical position in the duct. A simple model based on single particle behaviour was developed. The predicted solid temperatures agreed well with the experimental results. However, the predictions for the gas temperatures were less satisfactory.

1. Introduction

A system with free-falling particle curtain in a gas stream has been used widely in the industry as a heat exchanger [10]. Numerous investigations have been conducted to understand the heat transfer of free falling particle curtain in quiescent air, counter-current flow and cross-flow gas. For example, Hruby et al. [3] used a free-falling particle curtain as the direct absorber of the solar energy. Frain et al. [4] proposed the use of falling-bed heat exchanger for the heat recovery and regeneration in power plant. In this arrangement, solid particles fell through a vertical column against a counter-flowing gas stream. Shirley et al. [13] used a rotary drum to cool the melt granulation of urea.

One of the main factors found to significantly influence the heat transfer in particle curtain was the solid concentration. For example, Hruby et al. [3] investigated the effect of solid concentration on the heat transfer of a free falling particle curtain. Heat was exchanged between the falling particles and air within the curtain. The authors found that as the curtain's solid concentration increased, the particle temperatures also increased. The increased in solid concentration also led to a higher air temperature within the curtain. The authors suggested that the higher air temperature was primarily due to increase in heat transfer from the solids to the surrounding air as a result of increased solid concentration. The authors further suggested that increasing the solid concentration also increased the relative particle velocity. This reduced the time (particle–air contact time) available for heat to transfer from the particles to the surrounding air. The authors concluded that poor air–solid interaction led to poor heat transfer.

Frain et al. [4] investigated the heat transfer of particle curtain falling in a vertical column against a counter-flowing gas stream where the gas superficial velocity was less than the terminal velocity of the particle. Heat was exchanged between the falling particles and rising gas. The authors compared the heat transfer at the top and at the bottom of the heat exchanger. They also compared the heat transfer rate at the centre of the column and near to the wall of the column. The authors found that the heat transfer rate at the bottom of the column was higher than the top of the column, and the heat transfer rate near the wall of the column was lower than the centre of the column. They suggested that this was due to the variation in particle–gas interaction. At the top of the column, the particle–gas interaction was found to be poor, therefore led to low heat transfer rate. Whereas at the bottom of the column, the particle–gas interaction was found to be good, hence resulting in an improved heat transfer rate. The authors also found solid concentration variation in the column's axial direction. The authors reported that the solid concentration at the centre of the column was higher than the solid concentration near to the wall. They concluded that the interaction between particle and gas had a direct influence on heat transfer. This is in agreement with Hruby et al. [3] observations.

The study of a free-falling particle curtain in a horizontal gas flow appeared in numerous rotary drum studies. The interior surface of the drum is usually fitted with flights which elevate the particles and allow them to cascade through the gas stream as the

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drum rotated. The cascading particles formed curtains which are parallel to the length of the drum and free spaces are generated in between the cascading curtains. The gas stream flows parallel to the main plane of the particle curtains. Experimental studies showed most of the horizontal gas flows in the free space between the particle curtains instead of flowing through the particle curtains [5,6,11].

Schofield and Glikin [12] attempted to correlate the heat transfer in a rotary cooler in terms of a film heat transfer coefficient and the interfacial contact area between gas and solid. The authors found that this correlation overestimated the experimental results. The authors argued that this was due to the poor gas–solid interaction. The authors found that at the top of the particle curtain where the interaction between the solid and gas was poor, the gas temperature quickly reached equilibrium with the solid surface temperature. Whereas at the bottom of particle curtain where there was a higher degree of gas–solid interaction, the gas film became the controlling heat transfer resistance. These findings agreed with the findings of Saeman and Mitchell [11].

Hirosue and Mujumdar [14] investigated the influence of solid concentration on the volumetric heat transfer coefficient in rotary dryers and coolers. The authors found that the volumetric heat transfer coefficient of a low solid concentration curtain was close to the heat transfer coefficient estimated by single particle correlation (Ranz–Marshall equation). As the solid concentration increased, the Ranz–Marshall equation over estimated the volumetric heat transfer coefficient. The authors suggested that for a dilute system, the particles were in good contact with the air stream. As the particle concentration increased, the particle–air contact reduced accordingly.

From all of the investigations mentioned above, a good interaction between the gas and the particle is essential to provide a good heat transfer. Particularly in the studies of rotary drum, the majority of gas flows in the free space between the particle curtains instead of flowing through the particle curtains, thus reducing the contact efficiency between the gas and the solid. In the present study, a particle curtain is generated to span across the *entire* width of the duct and the gas flow is horizontal and perpendicular to the main plane of the curtain. Since there is no free space between the wall and the particle curtain, gas is forced to flow through the dilute curtain (high voidage). The aim of our study is to investigate the heat transfer between the gas and the particle curtain under these conditions.

2. Experiment

A schematic diagram of the experimental setup was shown in Fig. 1. The apparatus consisted of the following parts: a duct, air

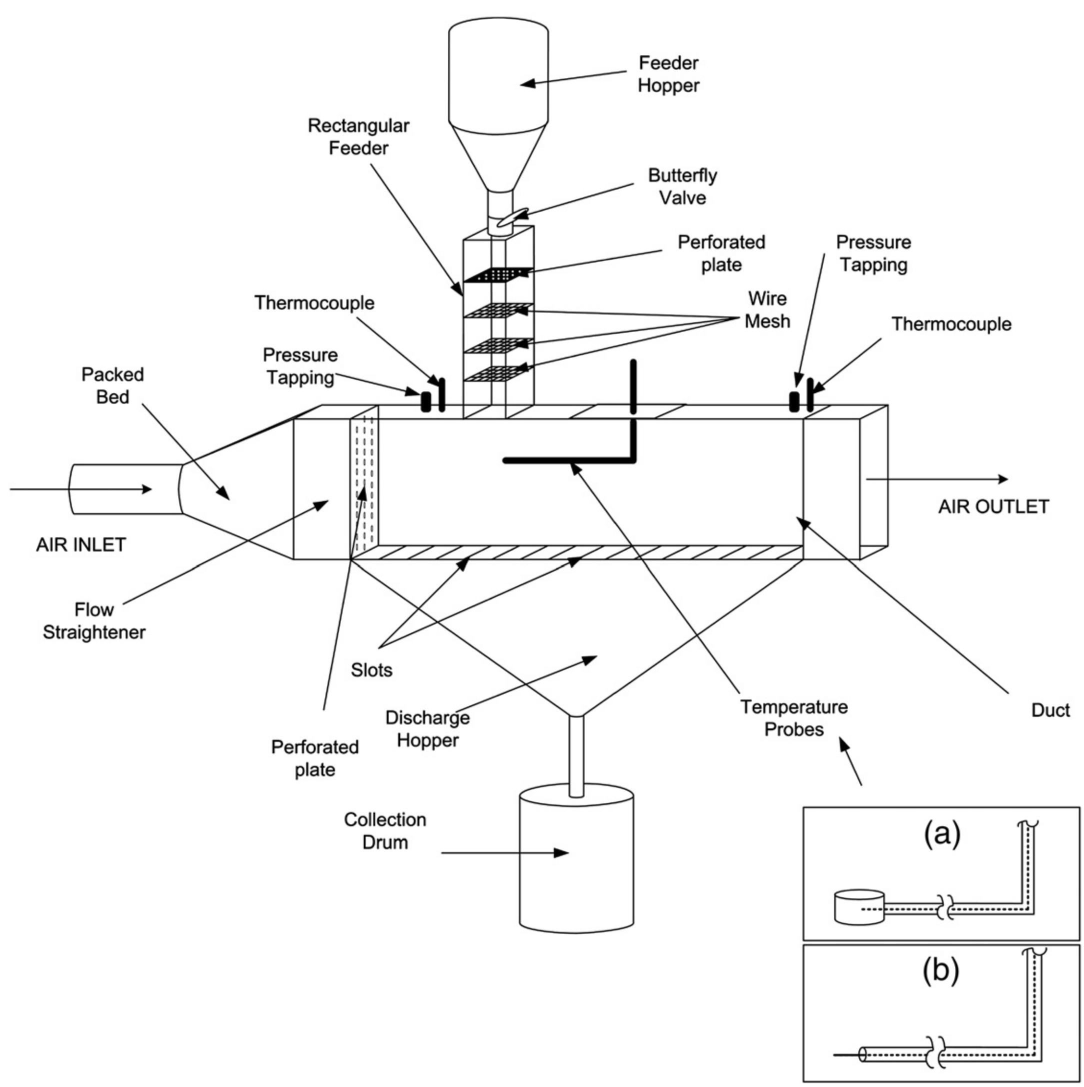

Fig. 1. A schematic diagram of the experimental setup, also shown the diagram of temperature probes: (a) solid temperature and (b) gas temperature.

Table 1
Properties of air used in the experiment and calculation

		T_g = 20 °C	T_g = 100 °C
Air Viscosity	[Pa s]	18.16×10^{-6}	21.9×10^{-6}
Air Conductivity	[W/m K]	25.9×10^{-3}	32.1×10^{-3}
Air Heat Capacity	[J/kg K]	1005	1009
Air Density	[kg/m^3]	1.205	0.946

supply system, solid feeder, solid transport system, collection drum, and measurement system. The duct had cross-sectional dimensions of 0.15 m width, 0.60 m height and a length of 2.40 m in the direction of air flow. The side walls of the duct were made of transparent Perspex. At the base of the duct, slots which could be opened or closed were installed to create a smooth wall at the bottom of the duct. During each experiment, most of the slots were closed, except those at the specific location where the particle curtain lands.

The airflow to the duct was provided by a Rootes-type positive displacement blower. Using electrical heaters, the air was pre-heated to the desired temperature before entering the duct. In order to minimise the gas swirl before entering the duct, a packed bed was installed in the transformation section connecting the 150 mm diameter pipe to the rectangular entrance to the duct. The packed bed was made from randomly-packed, 25 mm lengths of 25 mm i.d PVC tube with 2 mm wall thickness. A flow straightener was installed immediately downstream of the packed bed to produce an even gas velocity distribution across the duct cross-section. Air velocities in the range of 0.9 m/s to 1.2 m/s with a uniform velocity profile were used in the experiments. The gas velocity profile immediately downstream of the particle curtain was measured using a pitot tube connected to the pressure transducer. The tip of the pitot tube was positioned at the desired location where the gas velocity was to be measured.

A curtain of particles with steady mass flow rate and uniform particle distribution was created by steadily feeding solids from a hopper through a rectangular feeder in which a perforated plate and three pieces of wire mesh were secured. Uniform and steady curtains with various curtain thicknesses could be created by adjusting the dimensions of feeder. The mass flow rate of the particle curtain was varied by controlling the hole size of the perforated plate. A constant particle hold up was generated to ensure a constant solid mass flowrate. The particles stored in the hopper were discharged from the duct and collected in a collection drum located underneath the duct. Solids caught in the collection drum after experiments were transferred back pneumatically to the hopper before the start of new experiments. The capacity of the hopper was approximately 500 kg of solid particles. In the setting for this investigation, the particle mass flowrate could be varied from zero to 0.1 kg/s.

Experiments were conducted using the apparatus to heat up the solid with hot air from the ambient temperature. At the start of an experiment, the appropriate perforated plate was installed to establish the required mass flowrate. On top of the perforated plate, a constant solid hold up was established. The perforated plate with a uniform distribution of holes was designed to distribute the solid flow across the rectangular opening. The wire meshes were used to further disperse the solid flow. The dimension of the feeder opening (located at the point where the solids enter the duct) was adjusted to the desired size to obtain the initial curtain thickness (in the direction of air flow). A range of curtain thickness (4 cm to 10 cm) and mass flow rate (0.031 kg/s to 0.040 kg/s) were studied in the investigations.

The air flowrate was then established by adjusting the opening of the air-purging valve downstream of the blower to allow the correct amount of air to pass through the duct. The air temperature was then established by setting the desired temperature on the temperature controller. Once the air temperature stabilised, the butterfly valve was opened to allow particles to fall from the hopper. The opening of the butterfly valve located beneath the solid feed hopper was then adjusted to create a constant hold up on top of the perforated plate. The initial vertical particle velocity entering the duct from the feeder was obtained by capturing the particle positions with a high-speed camera (at 1930 frames per second). The particle curtain was imaged through the front wall of the duct using a high-speed camera. The camera was mounted on a platform that allowed the camera to be adjusted vertically and horizontally. The lens' focus was adjusted so that the individual particle at the centreline of the particle curtain was clearly captured by the camera. The captured images were analysed using ImageJ 1.37c software where the position of particle was then tracked frame by frame.

The particle and gas temperatures were measured as a function of vertical position in the duct using temperature probes. The temperature probes were attached to a platform on top of the duct. The probes were adjustable in both the horizontal and vertical directions. This allowed the temperature probes to be positioned at any elevation and distance from the particle curtain. Two types of temperature probe were used in the experiments. The first temperature probe was specifically designed for measuring the particle temperature. This temperature probe essentially consisted of a sampling cylinder cup (15 mm high and 20 mm in diameter) fitted with a bare type K thermocouple (Fig. 1(a)). A 3 mm diameter hole was drilled at the bottom of the sampling cup to allow a steady flow of particles to escape. This created a constant hold-up when the cup was placed inside the particle curtain. Disturbance of the particle curtain by the sampling cup was found to be small. The second temperature probe was used for measuring the gas temperature (Fig. 1(b)). This was essentially a bare type K thermocouple fixed at the tip of a metal probe. The exit gas temperatures were measured by placing the temperature probe at the downstream (at a specific height) of the particle curtain. The measurements of solid temperature using a sampling cup fitted with a type K thermocouple and air temperature with a type K thermocouple have been successfully used by Hruby et al. [3].

The particle used in this experiment was silica sand with Sauter diameter of 204 µm. The solid properties were assumed to be constant throughout the experiments and calculations (Table 1). The air properties were dependent on the inlet gas temperature (Table 2). The air properties between T_g = 20 °C and T_g = 100 °C were calculated by interpolation.

3. Modelling the curtain heat transfer

Models of gas–particle heat transfer in a cross-flow moving packed bed and fluidised bed heat exchanger were developed by McGaw [8,9]. The models were used to describe the process of heat transfer when gas was blown vertically upwards through a particle bed. These models were modified for the present study to

Table 2
Properties of solid used in the experiment and calculation

Solid	Silica sand	
Sauter mean particle diameter	204	µm
Particle density	2640	kg/m^3
Particle conductivity	0.33	W/m K
Particle heat capacity	753.1	J/kg K

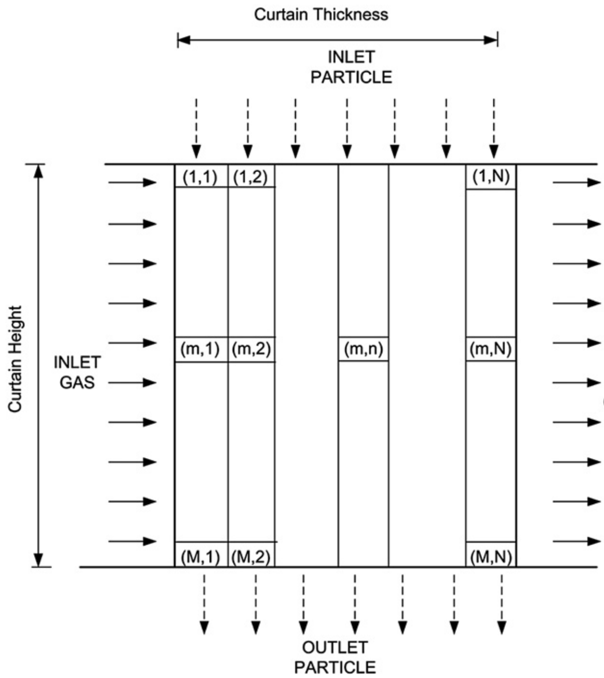

Fig. 2. Illustration of the division of the curtain into a two-dimensional array of elements.

describe the process of heat transfer in a cross-flow falling particle curtain heat exchanger. The clustering of particles was not observed during the experiment and it was not considered by the model.

In the current study, gas with a uniform velocity profile flows horizontally through a duct and a stream of particles was fed vertically into the duct from above to form a curtain across the entire width of the duct. In the model, the curtain was assumed to fall vertically. This curtain was then divided into a two-dimensional array of elements with equal size (Fig. 2). The particle curtain was split into M horizontal sections and N vertical sections along the height and thickness of the curtain respectively. Each element could be identified by its locations on the horizontal and vertical sections (m,n).

In each element, the numbers of particles were assumed to be constant and individual particles were assumed to fall vertically through the curtain with constant velocity, v_s. The gas entering the curtain was assumed to flow horizontally through the curtain with uniform gas velocity profile. The superficial gas velocity, v_g was assumed to be constant throughout the curtain. In the current study, the analysis was carried out for the case of heating the particles with hot gas.

The heat balance calculations were carried out initially on the first vertical section (n=1), starting from the top of the curtain (element (1,1)) to the bottom of the curtain (element (M,1)). The unsteady-state heat transfer was assumed to take place within the particles and heat was transferred from the gas to the particle surface by convection. In each element, the unsteady state heat transfer was assumed to take place for the duration of the gas contact time in the element, t_c.

$$t_c = \frac{\text{curtain thickness}}{v_g N} \tag{1}$$

In order to make sure the gas–solid contact time was consistent in the horizontal and vertical direction, the number of horizontal section (M) in the particle curtain was determined as follow:

$$M = \frac{\text{curtain height}}{v_s t_c} \tag{2}$$

All particles entered the first horizontal section of the curtain with a constant temperature and without internal temperature gradients. The gas entered the first vertical section of the curtain with a constant temperature.

A model on the transient heat transfer of spherical particles [1] was used to calculate the particle internal temperatures, T.

$$\frac{\partial u}{\partial t} = D\frac{\partial^2 u_r}{\partial r^2} \tag{3}$$

where $D = \frac{k_s}{\rho_s C_s}$ and $u = T \times r$.

Crank–Nicolson finite difference technique [2] was used to solve Eq. (3) for the duration of gas contact time in each element, t_c. The boundary conditions used in this technique were as follows

- At the centre: r=0, u=0
- At the surface, the heat is transferred by convection from the gas to the particle surface:

$$k_s\frac{\delta T}{\delta r} = h\left(T_{gi(m,n)} - T_{s(m,n)}\right) \tag{4}$$

where the film heat transfer coefficient for a spherical particle was calculated as follows [7]:

$$h = \left(\frac{k_g}{d_p}\right)\left(2 + 0.6\left(\frac{d_p v_g \rho_g}{\mu_g}\right)^{1/2}\left(\frac{C_g \mu_g}{k_g}\right)^{1/3}\right) \tag{5}$$

The mean particle temperature, T_{ave} leaving each element was obtained by calculating the volume weighted average of the internal temperature of particle at the end of the contact time.

$$T_{ave(m,n)} = \frac{\sum_{r=0}^{R} T_r V_r}{\sum_{r=0}^{R} V_r} \tag{6}$$

The heat balances were then used to calculate the gas temperature leaving each element. The heat absorbed by particles in element (m,n):

$$Q_{(m,n)} = \dot{m}_s C_s\left(T_{ave(m,n)} - T_{si(m,n)}\right) t_c \tag{7}$$

The heat released by the gas in element (m,n):

$$Q_{(m,n)} = \dot{m}_g C_g\left(T_{go(m,n)} - T_{gi(m,n)}\right) t_c \tag{8}$$

where the gas mass flowrate could be obtained as:

$$\dot{m}_g = \rho_g v_g \varepsilon A \tag{9}$$

where A is the element vertical cross-sectional area. The particle curtain's voidage, ε, can be calculated from: $\varepsilon = 1 - \frac{\dot{m}_s}{\rho_s v_s A_c}$.

Table 3
A summary of energy balances of the experiments and the model predictions

Curtain thickness (cm)	Solid mass flowrate (kg/s)	Inlet article velocity (m/s)	Inlet curtain voidage	Air inlet velocity (m/s)	Qgas (kW)	Qsolid (kW)	Qmodel (kW)
4	0.042	1.4	0.998	0.9	−0.69	0.69	0.72
4	0.042	1.4	0.998	1.2	−0.98	0.98	0.91
5	0.031	1.4	0.999	1.2	−0.78	0.77	0.79
6	0.041	1.4	0.999	0.9	−0.77	0.76	0.82
6	0.041	1.4	0.999	1.2	−0.98	0.98	1.00
10	0.040	1.3	0.999	0.9	−0.70	0.68	0.71

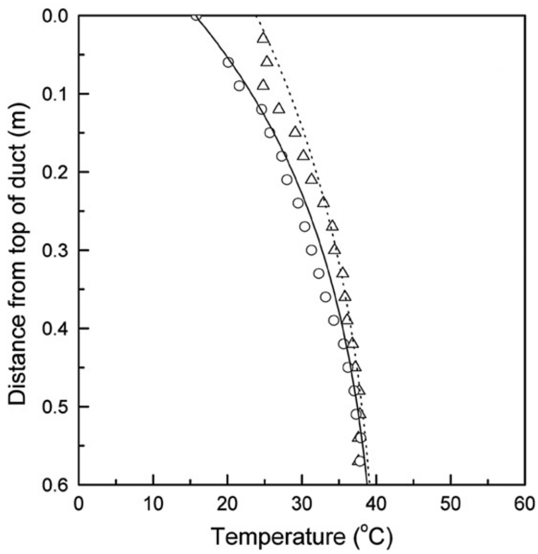

Fig. 3. Model prediction and experimental data of gas and solid temperature for particle curtain with gas velocity of 0.9 m/s, inlet thickness of 4 cm, and solid mass flowrate of 0.040 kg/s. Inlet solid temperature = 15.8 °C and inlet gas temperature = 41.3 °C. (○ Solid (exp), Δ Gas (exp), ▪▪▪ Gas model and — Solid Model).

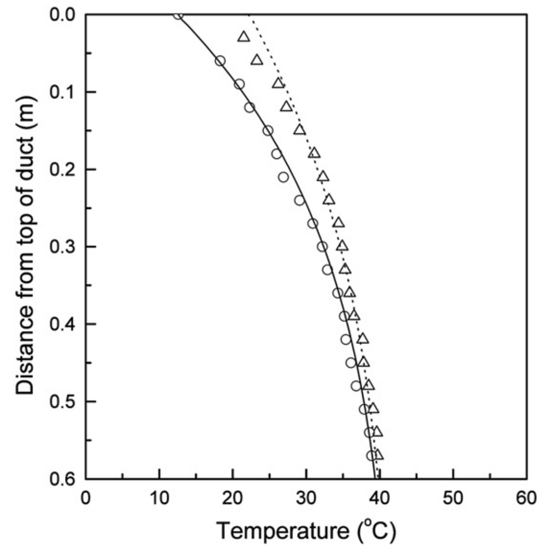

Fig. 5. Model prediction and experimental data of gas and solid temperature for particle curtain with gas velocity of 0.9 m/s, inlet thickness of 6 cm, and solid mass flowrate of 0.040 kg/s. Inlet solid temperature = 12.6 °C and inlet gas temperature = 42.5 °C. (○ Solid (exp), Δ Gas (exp), ▪▪▪ Gas model and — Solid Model).

The gas outlet temperature was then calculated by equating Eqs. (7) and (8):

$$T_{go(m,n)} = T_{gi(m,n)} + \frac{\dot{m}_s C_s \left(T_{ave(m,n)} - T_{si(m,n)}\right)}{\dot{m}_g C_g} \tag{10}$$

The solid temperature leaving horizontal section m was obtained as follow:

$$T_{so,m} = \frac{\sum_{n=1}^{N} T_{ave(m,n)}}{N} \tag{11}$$

Once the calculation of the first vertical section was completed, the same procedure was then repeated for the second and subsequent vertical sections. The particles entered the second and subsequent horizontal sections with uneven internal temperature distributions, which were taken as those calculated from the above elements. The gas entered the second and subsequent vertical sections with an uneven temperature distribution, which were taken as those calculated from the previous element in the same horizontal section.

4. Result and discussion

The rates of heat transfer from the gas to the particles were calculated using the measured inlet and outlet temperatures and mass flowrates of both streams (using Eqs. (9) and (10). Table 3

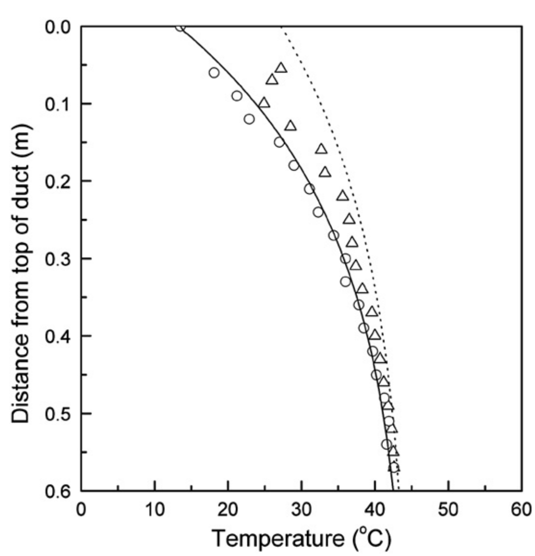

Fig. 4. Model prediction and experimental data of gas and solid temperature for particle curtain with gas velocity of 1.2 m/s, inlet thickness of 4 cm, and solid mass flowrate of 0.040 kg/s. Inlet solid temperature = 13.5 °C and inlet gas temperature = 45 °C. (○ Solid (exp), Δ Gas (exp), ▪▪▪ Gas model and — Solid Model).

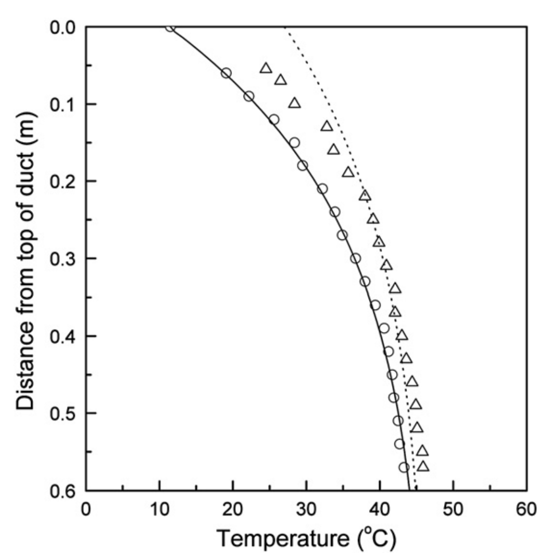

Fig. 6. Model prediction and experimental data of gas and solid temperature for particle curtain with gas velocity of 1.2 m/s, inlet thickness of 6 cm, and solid mass flowrate of 0.040 kg/s. Inlet solid temperature = 11.5 °C and inlet gas temperature = 46.8 °C. (○ Solid (exp), Δ Gas (exp), ▪▪▪ Gas model and — Solid Model).

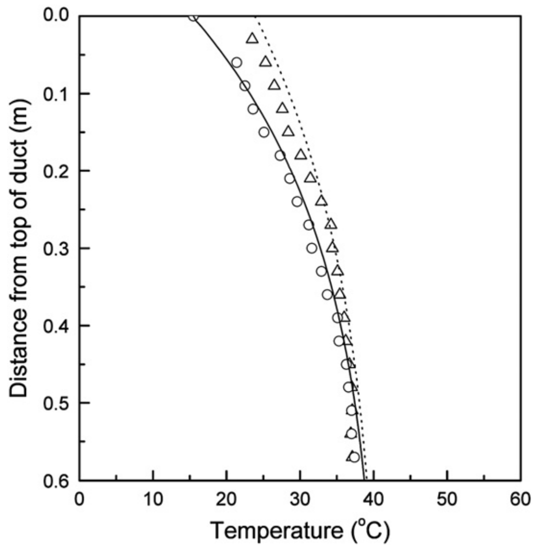

Fig. 7. Model prediction and experimental data of gas and solid temperature for particle curtain with gas velocity of 0.9 m/s, inlet thickness of 10 cm, and solid mass flowrate of 0.040 kg/s. Inlet solid temperature = 15.5 °C and inlet gas temperature = 41.3 °C. (○ Solid (exp), Δ Gas (exp), ▪▪▪ Gas model and — Solid Model).

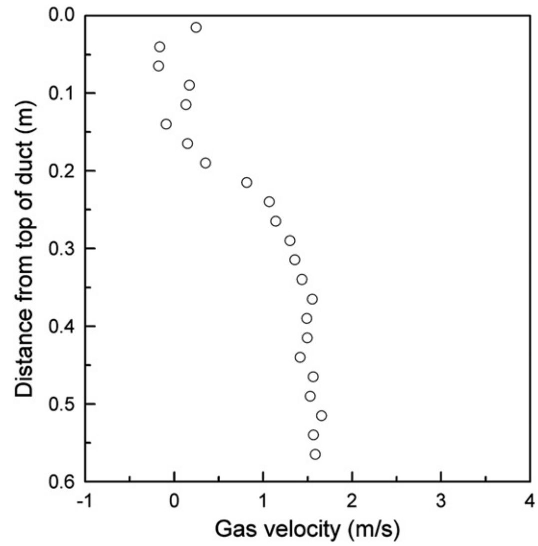

Fig. 9. A typical gas velocity profile at the trailing edge of particle curtain. Gas velocity profile at the trailing edge for particle curtain with solid mass flowrate of 0.031 kg/s, inlet thickness of 5 cm, and air velocity of 0.9 m/s.

summarises the energy balances of the experiments in this study. The rates of heat transfer predicted by the model were found to be in good agreement with the values calculated from the experiments. In addition, the measured rates of heat lost from the gas stream were also in agreement with the measured rates of heat gain by the solids.

In Figs. 3–8, experimentally measured gas outlet and solid temperatures are compared with the temperatures predicted by the model for a range of conditions. The simple model gave good prediction of the particle temperatures but predicted the gas outlet temperatures less satisfactory, especially at the top of the duct. This is thought to be due to the fact that, although the model assumed uniform gas flow, the actual gas velocity profile at the trailing edge of the curtain was not uniform. A typical gas velocity profile at the trailing edge of the curtain is shown in Fig. 9.

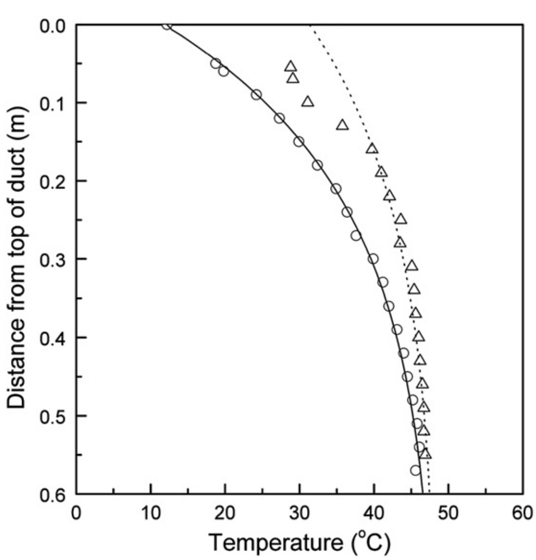

Fig. 8. Model prediction and experimental data of gas and solid temperature for particle curtain with gas velocity of 1.2 m/s, inlet thickness of 5 cm, and solid mass flowrate of 0.031 kg/s. Inlet solid temperature = 12.2 °C and inlet gas temperature = 48.7 °C. (○ Solid (exp), Δ Gas (exp), ▪▪▪ Gas model and — Solid Model).

5. Conclusion

An experimental study of the heat transfer of a dilute particle curtain falling through a horizontal gas stream was presented. The particle curtain spanned across the entire width of the duct, with no free space between the curtain and the duct walls. A simple model, based on single particle behaviour, was developed for this study. Despite the simplicity of the model, the predicted solid temperatures as a function of falling height gave good agreement with measured values over the range of conditions studied. However, the model predictions of the gas temperatures were less satisfactory, particularly in the upper regions of the curtain; this is thought to be due to that fact that in practice the gas flow is non-uniform across the curtain height, whereas the model assumes uniform flow. This is the subject of further study.

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Glossary

t_c: Contact time in each element, s
d_p: Particle diameter, m
a: Particle radius, m
δr: Radius increment in Crank–Nicolson finite difference, m
r: Particle radius, m
r_i: Distance measured from the centre to point *i* within particle, m
v_g: Gas Velocity, m/s
v_s: Particle Velocity, m/s
N: Number of vertical section in 2-D array of curtain element
M: Number of horizontal section in 2-D array of curtain element
T: Solid Temperature, °C
$T_{gi(m,n)}$: Inlet gas temperature of element (m,n), °C
$T_{si(m,n)}$: Inlet solid temperature of element (m,n), °C
$T_{go(m,n)}$: Outlet gas temperature of element (m,n), °C
T_i: Solid temperature at r_i, °C
$T_{s(m,n)}$: Solid surface temperature of element (m,n), °C
δT: Difference between T_s and T at (radius − δr), °C
$T_{ave(m,n)}$: Outlet solid temperature of element (m,n) in 2-D array of curtain, °C
$Q_{(m,n)}$: Amount of heat transferred in element (m,n), J
k_s: Particle conductivity, W/m K
k_g: Gas conductivity, W/m K
ρ_s: Particle density, kg/m^3
ρ_g: Gas density, kg/m^3
C_s: Particle heat capacity, J/kg K
C_g: Gas heat capacity, J/kg K
μ_g: Gas viscosity, Pa s
h: Film heat transfer coefficient, W/m^2 K
ε: Curtain voidage = $1-\left(\frac{\dot{m}_s}{\rho_s v_s A_c}\right)$
A_c: Curtain cross-sectional area = (curtain width × curtain thickness), m^2
$\dot{m}_s$: Solid mass flowrate, kg/s
$\dot{m}_g$: Gas mass flowrate, kg/s
A: Element cross-sectional area = $\left(\frac{A_c}{N}\right)$, m^2
V_i: Volume of an onion ring section, m^3 = $(4/3)\pi\left(r_i^3-r_{i-1}^3\right)$
n: Number of onion ring sections in a particle = $a/\partial r$
D: Thermal diffusivity, m^2/s = $\frac{k_s}{\rho_s C_s}$