Refereed Proceedings

The 13th International Conference on Fluidization - New Paradigm in Fluidization Engineering

Engineering Conferences International *Year* 2010

SHEAR-ASSISTED FLUIDIZED BED POWDER-COATING

Piero Bareschino* Francesco Pepe† Piero Salatino‡

*Università degli Studi del Sannio, piero.bareschino@unisannio.it
†Università degli Studi del Sannio, francesco.pepe@unisannio.it
‡Universita' degli Studi di Napoli Federico II, salatino@unina.it

SHEAR-ASSISTED FLUIDIZED BED POWDER-COATING

Piero Bareschino[1], Francesco Pepe[2], Piero Salatino[3]

[1] Dipartimento di Ingegneria, Università degli Studi del Sannio, P.zza Roma 21, 82100, Benevento, ITALY; T:+39 0824305589, F:+39 0824325246, e-mail: piero.bareschino@unisannio.it
[2] Dipartimento di Ingegneria, Università degli Studi del Sannio, P.zza Roma 21, 82100, Benevento, ITALY; T:+39 0824305589, F:+39 0824325246, e-mail: francesco.pepe@unisannio.it
[3] Dipartimento di Ingegneria Chimica, Università degli Studi di Napoli Federico II, P.le Tecchio 80, 80125, Napoli, ITALY; T:+39 0817682258, F:+39 0815936936, e-mail: salatino@unina.it

ABSTRACT

This study addresses a novel concept of dense-fluidized bed coating of objects where the effectiveness of coating is promoted by the intentional and controlled establishment of shear flow around the object. The fluidized powder is sheared by the controlled oscillatory motion of the object with respect to the fluidized bed. The proof-of-concept is given with experiments carried out using a commercial powder specifically manufactured for dry coating applications in fluidized bed. Systematic analysis of the effect of different levels of shear rate on particle mobility/adhesion and effectiveness of coverage was performed. A simple descriptive model has been developed to provide a mechanistic framework for the interpretation of the results.

INTRODUCTION

Painting or coating of an object may be conveniently carried out by dense-bed powder-coating, a process which consists of dipping the object into a dense expanded or bubbling fluidized bed of fine powders so as to favour cohesion or adhesion of the bed material onto the surface. Compared with alternative solvent- or emulsion-based processes, dry powder-coating usually entails a much lesser environmental impact and possible savings associated with the use of dry powders. Fluidized bed coating can be accomplished either without or with the application of electrostatic fields (1). In conventional fluidized bed coating the object is dipped into the fluidized bed after pre-heating to a temperature slightly higher than melting or softening temperature of the coating powders. As the powder approaches the object surface, it softens or melts forming a coating layer whose thickness increases with dip time. Electrostatic fields may induce additional clamping forces between the particles and the object that further stabilize the coating (2). Accordingly, in the electrostatics-assisted fluidized bed coating process the powders (charged by the ionized fluidization medium) are attracted towards metallic objects that are at ground potential improving coverage and stability of the coating. One possible drawback of electrostatics-assisted fluidised bed coating is that the thickness and uniformity can be inadequate due to the presence of voids/pinholes on plain surfaces and/or poor

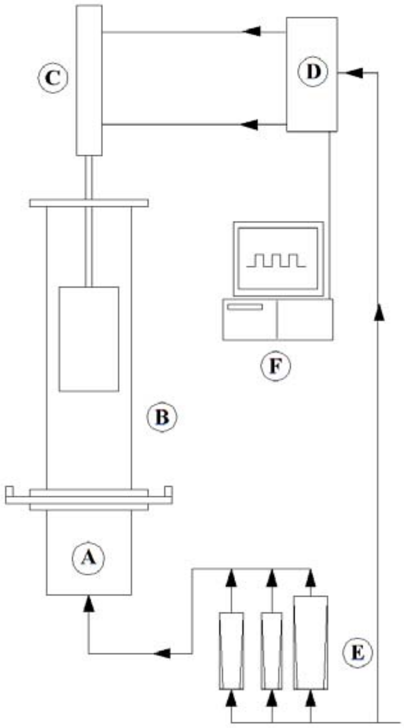

Figure 1 – Schematic view of experimental apparatus (not to scale): (A) wind box; (B) fluidized bed; (C) pneumatic cylinder; (D) electrovalve; (E) flow controller; (F) square wave generator.

coverage of inner angles, as reported in the literature (3). Several authors (4-7) systematically investigated the influence of process parameters (e.g. substrate pre-treatments, preheating methods, superficial gas velocity, dipping time, applied voltage) and powder properties on coating thickness and uniformity.

In the present study the dense-bed powder coating of objects is analyzed with a focus on the effect that intentional promotion of shear flow of the fluidized powder may exert on the effectiveness of coating. The basic concept is that shearing the emulsion phase of the bed at an appropriate intensity should enhance particle mobility, overcoming cohesive forces and disrupting the cellular structure typical of the particulate expansion of beds of group-A powders (8). The consequent augmented particle mobility should improve the uniformity and the effectiveness of coating.

Experiments have been carried out to obtain a preliminary proof-of-concept. To this end uncoated flat objects have been immersed in dense fluidized beds of a commercial powder, specifically formulated for fluidized-bed dry powder-coating applications. The novel feature of the experiments was represented by the fact that pre-set levels of shear rate at the surface of the object were induced by imposing oscillatory translational motion of the object of given amplitude and frequency. The effectiveness of coating was quantified by point-wise measurement of the reflectance of the coated surface as compared with that of the uncoated one. To this end an automated image analysis procedure was set up.

EXPERIMENTAL

Apparatus

The scheme of the experimental apparatus (not to scale) is reported in Fig. 1. It consists of a cylindrical fluidization column 120 mm ID and 280 mm high made of Plexiglas and equipped with a porous plate distributor. A vertical double-acting high-speed pneumatic cylinder was aligned with the column so that the specimen, a metallic sheet clamped to the shaft of the cylinder, could be immersed into the fluidized bed along its centerline. The cylinder is actuated by means of an electrovalve connected to a simple circuit generating a stable 12V peak-to-peak square wave at a pre-set frequency in the range 0 to 4 Hz in order to establish sheared flow conditions around the object. Gas superficial velocity is measured and controlled by means of mass flow meters.

A highly light-sensitive mega-pixel CMOS camera (space resolution 4000×3000 pixel) interfaced with a computer and controlled with an image processing software was employed to record the experiments. Post processing of images acquired was accomplished to obtain quantitative evaluation of the effectiveness of coating.

Materials and Operating Conditions

The fluidized bed consisted of a commercial powder specifically formulated for fluidized-bed powder-coating applications. The powder displayed delayed bubbling fluidization behaviour and negligible occurrence of channelling phenomena typical of group-C powders. The main properties of the powder are reported in Table 1.
The specimens were metallic sheets of rectangular shape, about 8cm x 30cm and about 2mm thick.
The fluidizing gas was technical air at ambient temperature. The gas superficial velocity was set at 2.1×10^{-3} m/s, that is 1.5 times the measured U_{mf} value.

Experimental Procedure

The gas velocity was adjusted to its pre-set value. After a few minutes, needed to ensure steady and even fluidization of the solids, the specimen was dipped into the bed for half of its length. Subsequently, the square wave generator was activated at a pre-set frequency in order to impose a vertical 1 cm amplitude oscillation to the specimen. When the time elapsed, the sheet was extracted from the bed and image-analyzed. The total duration of a dipping cycle was 12 seconds, including 1s to dip and 1s to lift the piece out of the bed. No electrostatic field was established during the experiments.

Table 1 - Properties of the granular solid investigated

Sauter mean diameter (d_p), μm	20
Size range, μm	10-100
Particle density (ρ_s), kg/m^3	2800
Incipient fluidization velocity (U_{mf})^1 , m/s	1.4×10^{-3}
Terminal velocity (U_t)^2, m/s	3.0×10^{-2}

(1) measured
(2) according to Haider and Levenspiel (9)

The analysis of the acquired images was based on a MATLAB® procedure: an algorithm was developed to automate the process of measuring the grey intensity of individual pixels in a selected area of the image overlapping with the specimen. The recorded data were worked out taking into account the stochastic nature of the local sample reflectance and expressed as cumulative frequency distribution (CFD) of the pixel grey intensity (or, equivalently, of the local sample reflectance). The value of grey intensity corresponding to the maximum of the CFD obtained from the analysis of a clean reference specimen was taken as the threshold between the coated and the non-coated regions of the specimen. The pointwise difference evaluated at the threshold between the value assumed by the CFD of the uncoated sample and that of a coated one is representative of the fractional coated area of the specimen.

RESULTS AND DISCUSSION

Figure 2 reports plots of the cumulative frequency distribution (CFD) of pixel grey intensities obtained in accordance with the image-analysis procedure. Plots refer to experiments in which the sample was subjected to oscillatory motion at frequencies ranging from 0 to 4Hz. The average reflectance of the uncoated reference specimen corresponded to pixel grey intensity of nearly 100, whereas the fully covered sample displayed pixel grey intensity of 256. Based on analysis of the reference uncoated specimen, the threshold pixel grey intensity was set at 180. Values of CFD corresponding to the threshold for the various plots represent the uncoated

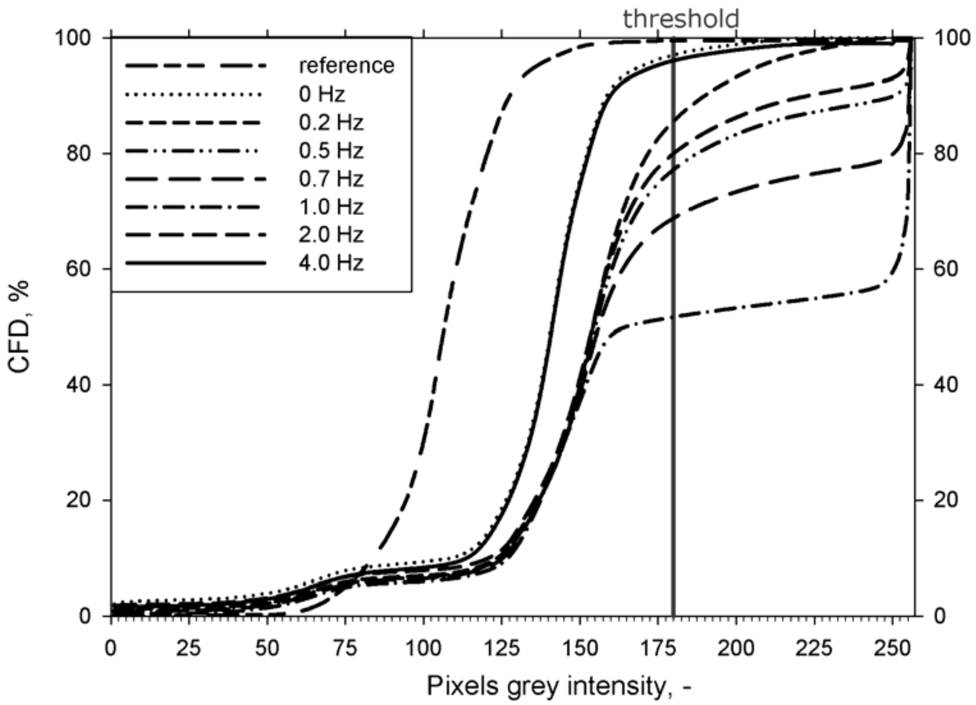

Figure 2 – Cumulative frequency distribution (CFD) of pixel grey intensities as a function of the frequency of vertical oscillations.

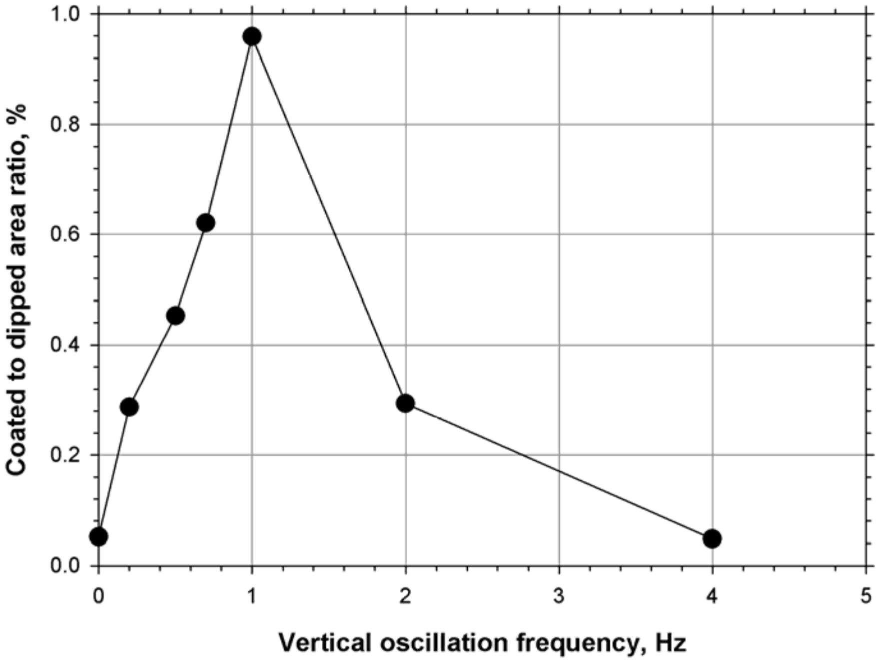

Figure 3 – Ratio between the fractional coated area of the sample and the fractional area of the specimen that was immersed in the bed as a function of vertical oscillation frequency.

fractional area of the sample for the given frequency of the oscillatory motion. The complement 100-CFD% represent the coated fractional area, to be compared with the fractional area of the sample that was actually immersed in the bed during the coating stage that was nearly 50% for all the experiments.
Data in Fig. 2 were worked out to obtain the ratio between the fractional coated area of the sample and the fractional area of the specimen that was actually immersed in the bed. Results are reported in Fig. 3. It is noteworthy that the effectiveness of coating is a non-monotonic function of the frequency of the oscillatory motion of the specimen. The “quality” of coating was maximum at an optimal frequency of about 1 Hz. At this frequency the ratio of the coated to the immersed areas of the sample approached unity (0.98).

A PHENOMENOLOGICAL MODEL OF SHEAR-ASSISTED SURFACE COATING

A simple descriptive model has been developed to provide a mechanistic framework of shear-assisted dense-fluidized bed powder-coating. The model was based on an analogy between gas adsorption and adhesion of cohesive particles to the surface of an object immersed into the bed, and represented according to the Langmuir isotherm. Particle adhesion is represented by the heterogeneous “reaction”:

$$S + P \xrightarrow{1} (SP) \qquad [1]$$

where S is the specimen surface, P is a “free” particle and (SP) the particle-surface “complex” formed upon adhesion.
The rate of reaction 1, expressed as the rate of surface coverage per unit exposed specimen surface area, is expressed as:

$$r_1 = k_1(1-\theta) \quad [=] \quad \frac{m^2}{m^2 s} \qquad [2]$$

where θ is the fractional surface that is already coated by particles and k_1 a kinetic constant. Bringing further the analogy with gas adsorption, the latter is assumed to depend on the local value of the “granular temperature” T, as defined by Goldhirsch (10), according to an Arrhenius-like expression:

$$k_1 = C_1 \exp\left(-\frac{E_1}{T}\right) \qquad [3]$$

where C_1 and E_1 are empirical parameters.
In turn, the granular temperature T may be related to the local level of the shear rate. According to Goldhirsch (10):

$$T = C\frac{\dot{\gamma}^2 d_p^2}{1-e^2} \qquad [4]$$

where C is a constant of order unity, $\dot{\gamma}$ the local value of the shear rate, d_p the particle size and e the coefficient of restitution associated with particle-to-particle collisions.
It is likely that the net particle adhesion rate results from dynamic equilibrium with a “backward” reaction consisting of particle detachment from the coated surface:

$$(SP) \xrightarrow{2} S + P \qquad [5]$$

The rate of reaction 2, expressed as the rate of surface that is uncoated per unit exposed surface area, is expressed as:

$$r_2 = k_2\theta \quad [=] \quad \frac{m^2}{m^2 s} \qquad [6]$$

Similarly to reaction 1, it can be assumed that:

$$k_2 = C_2 \exp\left(-\frac{E_2}{T}\right) \qquad [7]$$

where C_2 and E_2 are empirical parameters. From energetic arguments, it can be speculated that $E_1<E_2$, which implies that detachment is a stronger function of the granular temperature than adhesion.
A clean surface immersed into a dense fluidized bed will be coated at a rate given by:

$$r = r_1 - r_2 = k_1(1-\theta) - k_2\theta \quad [=] \quad \frac{m^2}{m^2 s} \qquad [8]$$

Accordingly, the fractional coated surface area of the specimen increases at a rate:

$$\frac{d\theta}{dt} = k_1(1-\theta) - k_2\theta \qquad [9]$$

which, integrated over the time interval [0,t], yields:

$$\theta(t) = \frac{k_1}{k_1+k_2}\{1-\exp[-(k_1+k_2)t]\} \qquad [10]$$

In the long term, a steady fractional coverage would be approached, given by the condition:

$$r = r_1 - r_2 = 0 \Rightarrow \theta_\infty = \frac{k_1}{k_1 + k_2} \qquad [11]$$

The proposed model suggests that, for any given exposure time, the fractional coated area of the specimen surface will depend solely on the granular temperature levels established on the object surface. Analysis of equation 10 indicates that, for a given exposure time t, the fractional coverage θ is a non-monotonic function of the granular temperature T. More specifically:

- for very low values of granular temperature T, "free" particles P do not overcome the cohesive forces which keep them bonded in the "cellular" structures typical of the expanded state of homogeneously fluidized beds of group-C and group-A powders. Accordingly, particles have limited mobility and are unable to reach the object surface, a feature that results into very poor coating levels;
- for very high values of T, the particles mobility is greatly improved. However extensive abrasion of the object's surface, essentially related to the "coherent" motion of the emulsion phase of the bed relative to the surface, may overcome the positive effect of enhanced particle mobility and deteriorate the level of coating by favouring the detachment of particles.

Though qualitative, the predicted non monotonic trend of the fractional coverage as a function of the granular temperature is consistent with the observations (Fig. 3). The agreement supports the soundness of the proposed phenomenological model.

CONCLUSIONS

The effectiveness of a novel concept to improve the quality of dense-fluidized bed powder coating of objects has been demonstrated. The concept is based on the intentional promotion of shear flow between the object and the emulsion phase of the fluidized bed, as a mean to improve the mobility of fluidized particles and enhance adhesion. Shear-flow is established by inducing the oscillatory motion of the immersed object at pre-set values of amplitude and frequency. The quality of powder-coating was quantified by point-wise measurement of the reflectance of the coated surface as compared with that of the uncoated one by means of an automated image analysis procedure.

Experiments have been carried out at pre-set levels of shear rate at the surface of the object, induced by imposing oscillatory translational motion of the object of fixed amplitude and frequency ranging between 0 and 4 Hz. Experimental results indicate that the quality of coating depends on the frequency of the oscillatory motion in a non-monotonic fashion. An optimal oscillation frequency of nearly 1 Hz yielded excellent quality of coating even in absence of electrostatic field.

A simple descriptive model, based on the analogy between gas adsorption and adhesion of cohesive particles to the surface of an object immersed into the bed, has been developed. The model provides a mechanistic framework for the interpretation of the experimental results. The model is able to represent the key qualitative features of the recorded phenomenology.

ACKNOWLEDGMENTS

Financial support to this study was granted by Whirlpool Europe. AKZO-Nobel is acknowledged for providing the coating powder used in the experiments.

REFERENCES

1) Richardson, J.F., Incipient fluidization and particulate systems, in: Fluidization, J.F. Davidson and D. Harrison eds., Academic Press, New York (1971).
2) Castle G.S.P., Industrial applications of electrostatics: the past, present and future, Journal of Electrostatics, 51-52 (2001).
3) Barletta, M., Tagliaferri, V., Influence of process parameters in electrostatic fluidized bed coating, Surface & Coatings Technology 200, 4619-4629 (2006).
4) Richart, D.S., A report on the fluidized-bed coating system - Part 1. Fluidized bed variables and their influences, Plastics Des. Tech. 2, 18–26 (1962).
5) Richart, D.S., A report on the fluidized-bed coating system - Part 2. Plastics for coating and their selection, Plastics Des. Tech. 2, 26–34 (1962).
6) Pettigrew, C.K., Fluidized bed coating - Part 1. Effects of fluidized bed variables, substrate pre-treatment and preheating method, Mod. Plastics 44, 111–117 (1966).
7) Pettigrew, C.K., Fluidized bed coating, - Part 2. Effects of dipping, post-heating and complex geometrical variables, Mod. Plastics 44, 150–156 (1966).
8) Massimilla, L., Donsì, G., Zucchini, C., The structure of bubble-free gas fluidized beds of fine fluid cracking catalyst particles, Chem. Eng. Sci. 27, 2005 (1972).
9) Haider, A., Levenspiel, O., Drag coefficient and terminal velocity of spherical and nonspherical particles., Powder Technol., 58, 63 (1989)
10) Goldhirsch, I., Introduction to granular temperature, Powder Technol., 182 (2), 130-136 (2008).