DRYING IN A VERTICAL PNEUMATIC BED: STUDY OF THE FLUID DYNAMIC AND HEAT TRANSFER

C. P. NARIMATSU
Graduate Program of Chemical Engineering
Federal University of São Carlos
C. P: 676 – ZIP CODE: 13569-265 – São Carlos/S.P
Phone: 55 – 16 – 260-8264
pcpn@iris.ufscar.br

J. T. FREIRE
Chemical Engineering Department
Federal University of São Carlos
C. P: 676 – ZIP CODE: 13569-265 – São Carlos/S.P
Phone: 55 – 16 – 260-8264
freire@power.ufscar.br

Abstract: The purpose of this research is to analyze the fluid dynamic and heat transfer behavior of vertical pneumatic transport bed, to further carry out the experimental investigation of the drying of porous and non-porous particles. The bed employed in the test is a 53.4mm diameter tube, made of galvanized iron and 4.1m long. The solids are fed into the tube by a gravitational feeder. Aluminum particles and glass spheres, both with mean diameter of 3.68mm have been used in the tests in order to study the influence of fluid dynamic behavior on gas-solid heat transfer in a vertical pneumatic transport bed. Experimental data allowed the characterization of the flow regimes, the determination of the temperature profiles and heat transfer coefficient. A numerical study was also carried out on the parametric sensitivity of the gas-solid heat transfer coefficient to volumetric air flow rate, solids flow rate and voidage.

Keywords*: pneumatic bed, heat transfer, heat transfer coefficient, fluid dynamic, flow regimes*

1. Introduction

The pneumatic drying is an important unit operation, in which the transport, heating and drying of particulate material occurs simultaneously. In this process, hot air, saturated vapor, overheated vapor (Blasco et al. 2000) or combustion gases supplies the drying energy and conveys the wet material along a duct. Pneumatic drying process usually occurs at low volumetric solid concentrations, $\varepsilon > 0{,}98$ (Rocha and Paixão, 1997), the tube wall may be insulated and the heat transfer occurs between the fluid and the particles.

In spite of the increasing number of pneumatic dryers in industries, the fundamental researches about drying are not having significant progresses. The design of such equipment is still based on empirical knowledge or numerical simulation of the mathematical models. Experimental data is scarce in order to confirm the validity of these models. Few works were found in literature focusing on the theoretical and experimental analysis of pneumatic drying, mainly concerning the understanding of complex heat and mass transfer phenomena involved in the process, particularly when the mass transfer occurs by internal moisture diffusion and when are employed particles with diameters having magnitude of millimeters.

The fluid dynamic of gas-solid suspension has been receiving great attention from the researches, mainly with relation the aspects such as the influence of diameter and density particles (Narimatsu and Ferreira, 2001; Hyder et al. 2000), the transport tube diameter and the solid feeding system (Costa, 2001; Hettiaratchi et al. 2000), on the characterization and identification of the flow regimes. The knowledge of the fluid dymamic behavior is very important in the study of heat transfer, once its mechanism are largely governed by the fluid dymamic flow conditions (Ma and Zhu, 2000; Basu and Nag, 1996).

The comprehension and mathematical description of the heat transfer mechanisms is also essential to the estimate of the heat transfer coefficient (h). Recent works involving the study of heat transfer in pneumatic beds are quite rare. The few works available adopt different operational conditions and many times use distinct materials, thus difficulting or even preventing the comparison among results. Besides, the analysis of the effects of variables such as density and diameter particles, air velocity on gas-solid heat transfer coefficient are still little frequent.

In this way, the present paper aims to investigate the fluid dymamic and thermal behavior in a vertical pneumatic bed, through the experimental analysis, to further carry out investigation of the drying and analyse of two-phase models.

2. Methodology

During the tests to choose the porous and non-porous particles to be used in this work, some points were considered: uniformity of size, wettability and small mass losses due to attrition during the transport.

Aluminum particles and glass spheres, both with mean diameter 3,68mm were used in the tests. Properties of the materials tested are listed in Table 1.

Tabela 1. Properties of materials tested.

properties	methodology	aluminum	glass
d_p (mm) - particle diameter	sifting	3.68	3.68
ρ_s (kg/m^3) - particle density	helium pycnometer/water pycnometer	3000	2500
ρ_a (kg/m^3) - apparent density	mercury porosimeter	1750	-
A_s (m^2/g) - surface area	B.E.T	227.90	-
V_p (cm^3/g) - pore volume	B.E.T	0.312	-
ε_p (%) - particle voidage	mercury porosimeter	24.47	-
Cp_s (kcal/kg ^{o}C) - solid specific heat	literature	0.20	0.18

The apparatus used in the experiments is shown in Fig. (1).

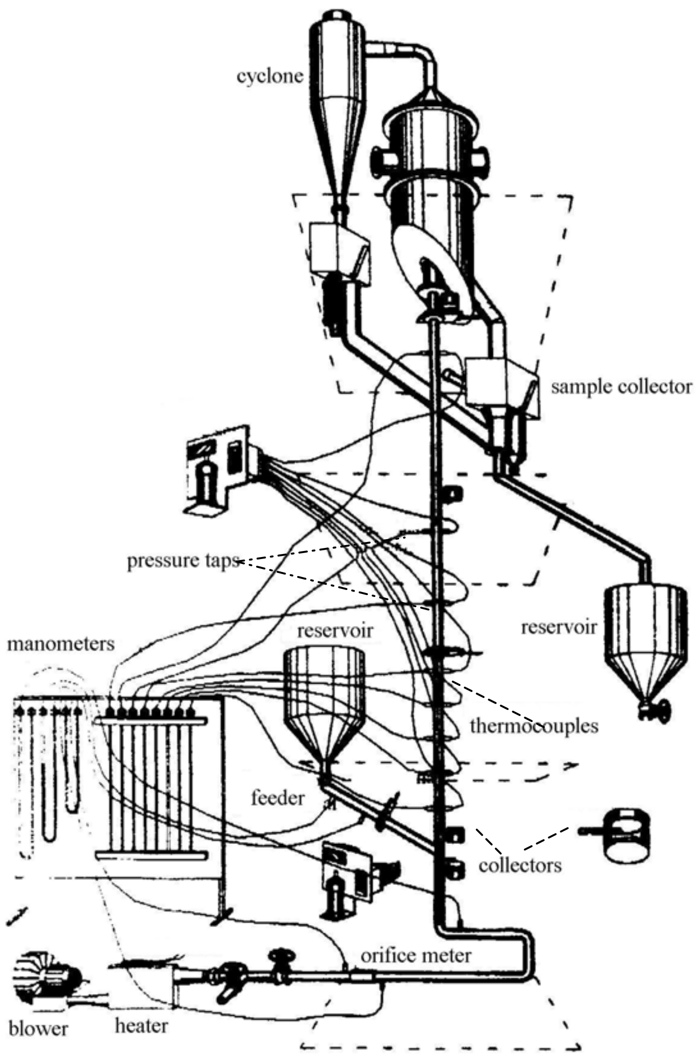


Figure 1. Experimental apparatus.

Particles are stored in a reservoir and introduced into the transport tube by means of a 65^0 angle inclined gravitational feeder. After, the particles are conveyed through a 53.4mm insulated galvanized iron tube 4.10m long.

Air is supplied to the system by a 7.5hp blower, and its volumetric flow rate was measured with an orifice flow meter. The heating is made by a heater, constituted by four eletric resistences of 1000W each. Resistences and air temperature are controlled by a digital temperature controller. A reduction nozzle was placed at the air inlet, aiming at reducing both the gas flow rate deviated through the feeder and the length of the acceleration region on the transport tube (Silva et al, 1996). The nozzle reduced the air inlet diameter from 53.4 to 32.0mm.

After being pneumatically transported, the particles return for another reservoir. The solids flow rate was measured by diverting the flow and collecting the solids in the sample collector. One cyclone Lapple-type is used to collect the dusts, they casually appear because of the solids attrition effects.

The static pressures along the tube were mensured at eight points (0.175, 0.475, 0.775, 1.075, 1.375, 2.175, 2.995 and 3.865m) by pressure taps connected to U-type manometers. These quotas were chose having how reference the solids inlet into drying tube (z = 0).

During the operation, the feeder was kept filled with solids and the gas flow rate through it was estimated from the Forcheimer equation (Massarani, 1997), with the pressure drop measured between two points of the feeder. The gas flow rate in the transport tube was obtained from a mass balance which considered the difference between the air supplied by the blower and the air deviated through the feeder, which in most cases was negligible. The length of the acceleration region was obtained from experimental data, by plotting the pressures versus axial distances of transport tube and taking the linear portion of the curves. This length was found to be less than 0.475m for all conditions investigated.

The axial profile of air temperature of the pneumatic dryer was mensured with nine thermocouples (T-type) with protection, where the first was introduced in the entrance of drying tube and the others eight thermocouples were located in identical quotas to the pressure taps. The solids temperature was determined using a calorimeter. Four colectors were installed along drying tube, in quotas same to 0.21, 0.82, 2.21 e 3.84 m. Larger details about the determination of gas and solids temperature measures they can be seen in Narimatsu et al. (2002).

Procedure for determination of ε e h

Voidage is determined through the momentum balance equation for the mixture (Capes and Nakamura, 1973; Ferreira, 1996), neglecting the particle-wall friction force (Littman et al. 1993; Wirth, 1995) and the acceleration region. The equations are given by:

$$-\frac{dp}{dz} = (1-\varepsilon)(\rho_p - \rho_g)g + \varepsilon \rho_g g + F_f \tag{1}$$

where:

ρ_p= particle density (kg/m^3);
ρ_g= air density (kg/m^3);
g= gravitational acceleration and
F_f= air-wall friction force.

Many authors used this methdology to determine the voidage (Mastellone and Arena, 1999; Lehner and Wirth, 1999; Issangya et al. 1999; Sundaresan and Kolar, 2002), and they still neglected the term of air-wall friction force. However, this term can be important in dilute phase flow. The estimates of voidages are carried out using experimental values of –dp/dz, and values of F_f estimated from the gas-phase momentum equation, with pressure gradients obtained for gas flow without particles.

From the energy balances between solid and fluid phase, using cylindrical geometry and assuming one-dimensional plug flow, steady-state flow, constant physical-chemical properties, the heat loss through the tube wall is neglected and the convection on the solid surface is the predominat mechanism of thermal exchange, it is possible to determine the gas-solid heat transfer coefficient. The differential equations that describe the energy balances to the two-phase model are:

$$Cp_g G_g \frac{dT_g}{dz} + hS[T_g(z) - T_s(z)] = 0 \tag{2}$$

$$Cp_s G_s \frac{dT_s}{dz} - hS[T_g(z) - T_s(z)] = 0 \tag{3}$$

with the following boundary conditions in the inlet region:

$$T_g(0) = T_{g0} \tag{4}$$

$$T_s(0) = T_{s0} \tag{5}$$

where:

Cp_g= air specific heat (kcal/kg°C);
G_s= solids mass flux (kg/m²s);
G_g= gas mass flux (kg/m²s);
h=gas-solid heat transfer coefficient (kcal/m²h°C);
T_g= air temperature (°C);
T_s= particle temperature (°C);

$$S=\frac{6(1-\varepsilon)}{\varphi\, d_p} = \text{particle surface area per unit bed volume } (m^{-1}), \tag{6}$$

φ= particle sphericity and
z= axial distance in the transport tube.

Through the Eq. (2) – (5), and the experimental measures of the air and solids flow rate, solids inlet temperature, axial profiles of air temperature and voidage values supplied by the Eq. (1), is possible to determine the gas-solid heat transfer coefficient.

In Table (2) the range of experimental conditions studied is illustrated.

Table 2. Range of variation in operational conditions.

variable	methodology	aluminum	glass
W_s (kg/s) - solids flow rate	sample collector	0.02462 – 0.04271	0.02437 – 0.04219
U (m/s) - superficial air velocity	orifice flow meter	15.18 – 30.15	18.64 – 29.73
-dp/dz (Pa/m) - total pressure gradient	static pressure profiles	191.53 – 431.41	226.09 – 504.08
ε (-) - voidage	balance equations	0.987 – 0.994	0.984 – 0.996

3. Results and Discussion

3.1. Fluid dinamic: identification of the flow regimes, effects of solids flow rate and particle density

The fluid dynamic of the gas-solid flow is quite complex. If the air velocity or solids holdup are varied, for instance, several flow regimes can be observed in pneumatic conveying (Leung, 1980). The experimental determination of the point in which the exact transition among those regimes cannot be detected during the experiments, then the relationship between the total pressure gradient and air velocity was adopted to identify the transition point between the dense and dilute phase.

Typical curves of total pressure gradient versus superficial air velocity are shown in Figure (2), for glass spheres (full points) and aluminum particles (empty points), with the same mean diameter and considering a fixed solids flow rate.

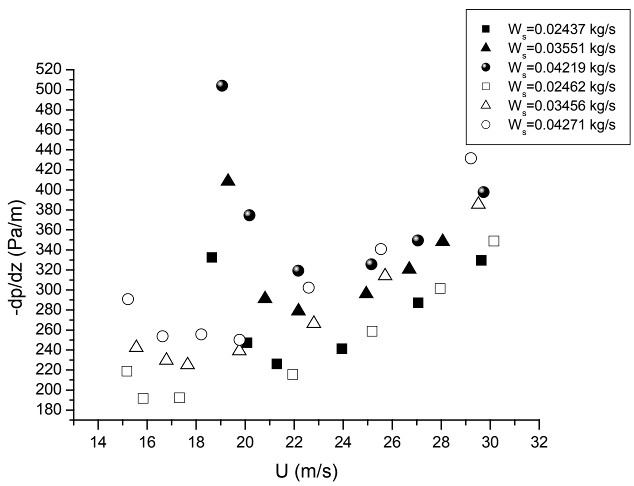


Figure 2. Total pressure gradient in the transport tube versus superficial air velocity for glass spheres and aluminum particles, in different solids flow rates.

The maximum value of air velocity was limited by blower capacity, while the lower values were set by the minimum air velocity requerid to transport the particles. The pressure gradient was determined from a linear fitting of the curves of static pressure versus axial distance in the transport tube, to the non-accelerated region.

Figure (2) shows similar qualitative behaviors for all the conditions investigated. Considering a fixed solids flow rate, the pressure gradient decreases with increasing air velocity until a certain value where it starts to increase again. This behavior is already well known and Marcus et al (1990) claim that this minimum point marks the transition between the dilute and dense phase flows in a pneumatic transport system.

The effects of solids flow rate can be also observed, because the pressure gradient increases as the solids flow rate is increased, considering a fixed air velocity and same material.

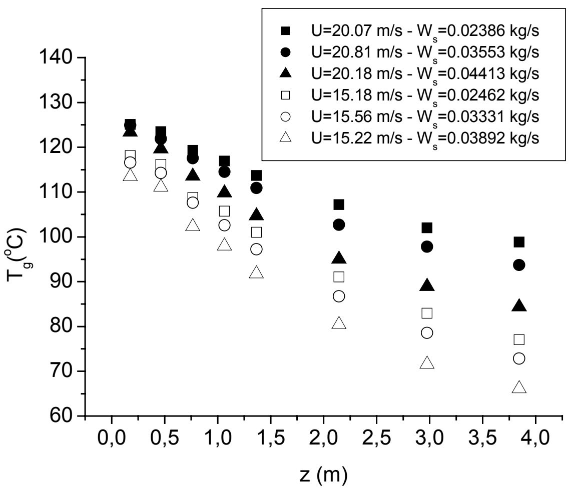
In Fig. (2) are compared the curves of –dp/dz versus U obtained for glass spheres and aluminum particles, it is verified that the locations of minimum pressure gradient points are affected by the particle density. For being a porous material, the density for aluminum particle is smaller than the glass spheres, resulting in differences in the locations of minimum points and in a wider range of dilute flow conditions. Data obtained at identical solids flow rates, one notes that in the dilute phase flow the pressure gradients are practically the same, indicating that at higher air velocities the effect of particle density was little significant. This behavior was also reported by Narimatsu and Ferreira (2001) and by Ravi Sankar and Smith (1986).

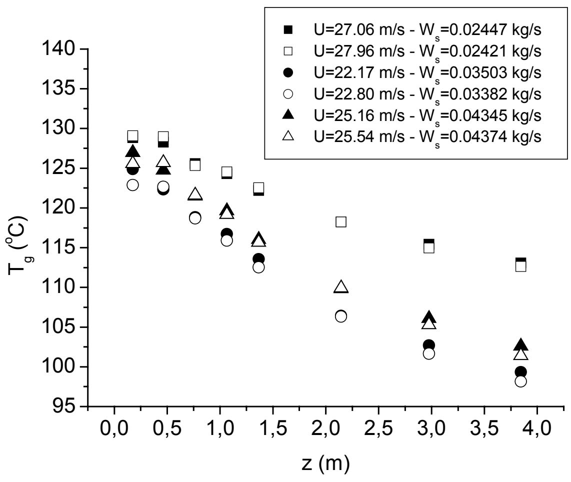
3.2. Heat Transfer

Concerning the heat transfer, the experimental profiles of air temperature and the gas-solid heat transfer coefficients were analyzed.

During all heat transfer experiments, dry solids were used (in the equilibrium moisture) and the digital controller was programmed to maintain the outlet temperature of heater around 140°C. Temperature values were registered when the process was at steady-state regime.

Figure (3-a) shows the air temperature profiles for the glass spheres (full points) and aluminum particles (empty points) at a similar air velocity and different solids flow rate. For each material and similar air velocities is observed that the highest are the solids flow rates, the more accentuated is the air temperature profile along the bed. During the experiments it could be noticed the tendency to the same solids flow rate, as lower the air velocity, it becomes the air temperature profile more prolonged. Therefore, it could be verified for gas-solid flow in pneumatic bed that the heat transfer is influenced by the solids holdup and also for the air velocity, because once increasing the solids holdup occurs an increase in the thermal exchange area and reducing the air velocity, will increase the time of residence of the solids in the bed and thus the convective heat transfer between the gas and solids. Figure (3-b) are shown the air temperature profile for glass spheres (full points) and aluminum particles (empty points), at similar operational conditions. It is noticed that the morphology of material (porous or non porous) did not influence in the profiles behavior of air temperature. The temperature profiles had similar behaviors when it was analysed particles with same diameter and same air velocity and solids flow rate.



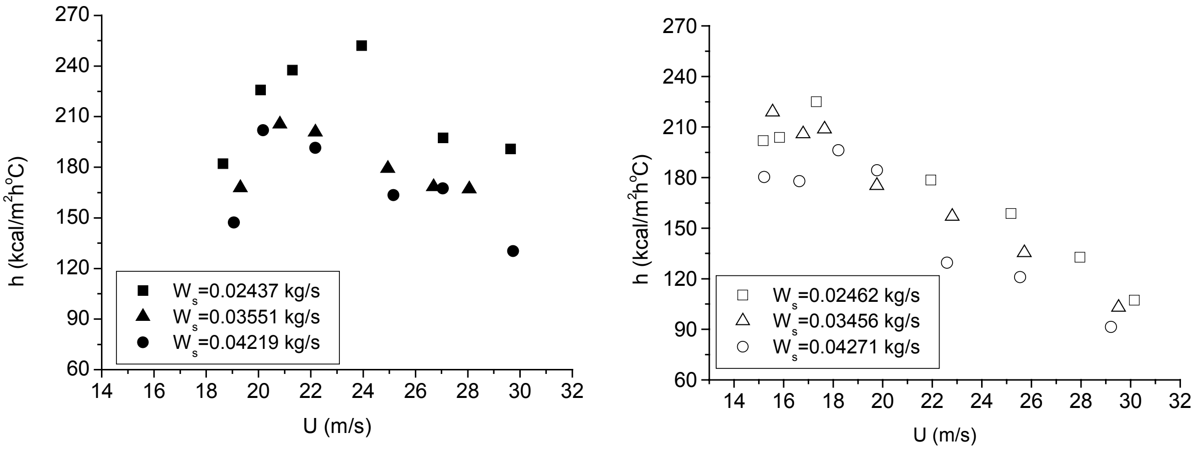


(a) (b)

Figure 3. Air temperature profiles for glass spheres and aluminum particles: (a) similar U and different W_s; (b) similar W_s and U.

Using Eq. (2)- (5) proposed in this work, through a non-dimensional, together with the experimental data of air and solids flow rates, solids inlet temperature, air temperature profile and voidage values supplied by the Eq. (1), it was determined the gas-solid heat transfer coefficient for glass spheres and aluminum particles.

Figure (4) are shown the data gas-solid heat transfer coefficient versus superficial air velocity, for glass spheres and aluminum particles, in different solids flow rates.



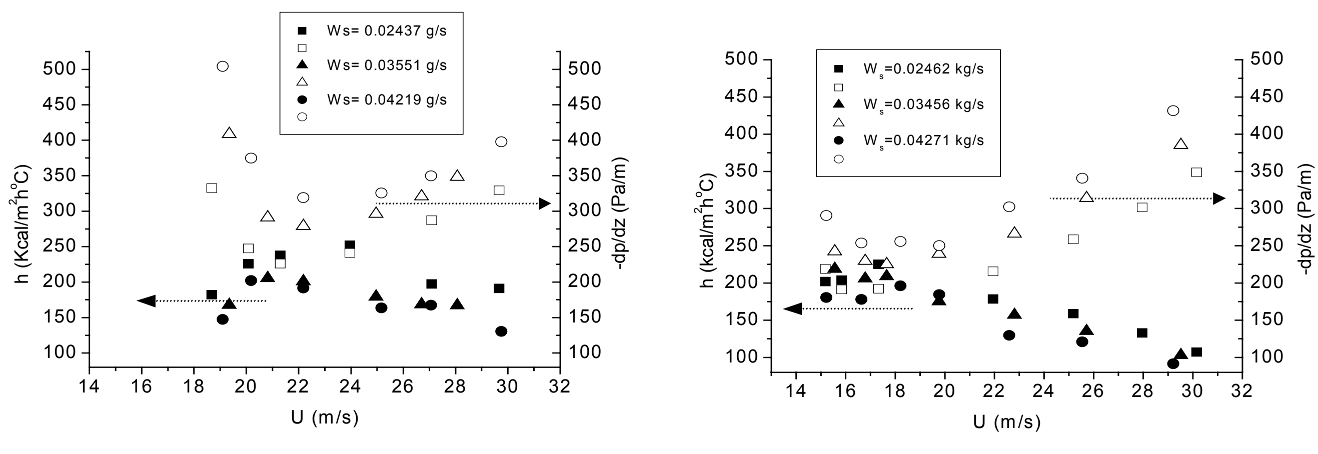
(a) (b)

Figure (4). Gas-solid heat transfer coefficient versus superficial air velocity, in different solid flow rates: (a) glass spheres (b) aluminum particles.

Through Fig. (4) is possible to verify the influence of the air velocity on the gas solid heat transfer coefficient. Most of curves, for glass spheres and aluminum particles, decreasing the air velocity occurs an increase of h, until reaching a maximum point, where those values tend to decrease again. This behavior is more accentuated for glass spheres.

Reviewing in the literature, until the moment, were not found works, which approached the effects of different variables (diameter and density particles; solids flow rate, air velocity and temperature) on the gas-solid heat transfer coefficient for vertical pneumatic beds. These analysis are usually found in studies about the heat transfer in other gas-solid contact system, such as fluidized bed, vibro-fluidized bed and spouted bed, which involve the heat transfer between the wall tube and suspension or the heat transfer between surface immersed into the bed and the suspension (Farag and Tsai, 1993; Gunn and Hilal, 1994; Macchi et al. 1999; Bi et al. 2000; Sundaresan and Kolar, 2002) so they do not involve the gas-solid heat transfer as in this work.

Figure (5) shows data of gas-solid heat transfer coefficient and total pressure gradient versus superficial air velocity, for glass spheres and aluminum particles, respectively, in different solids flow rates.



(a) (b)

Figure 5. The comparison between the data of h and –dp/dz versus U, in different solids flow rates: (a) glass spheres; (b) aluminum particles.

Analyzing Fig. (5) there is a certain influence of the fluid dynamic behavior on the heat transfer coefficient. Comparing the curves are noticed the increase of the gas-solid heat transfer coefficient occurs exactly in the transition region between the dense and dilute flow, i.e., in a region influenced by air velocity, which is responsible for the air convection along bed, as the increase of the solids holdup, which is responsible for the increase in the thermal exchange area of the particles.

Gas-solid heat transfer coefficient versus solid flow rate, for glass spheres (full points) and aluminum particles (empty points), in different air velocities are shown in Fig. (6). It is possible evaluate the effect of solids flow rate on the heat transfer coefficient behavior. Most of results of this work, considering in a same air velocity, as lower the solids flow rate, larger is the heat transfer coefficient. However, in spite of the existence of this tendency, the effect of variation of solids flow rate on the heat transfer coefficient is not shown so significant. Next item (3.3), it will be done a parametric sensitivity analysis more signficant.

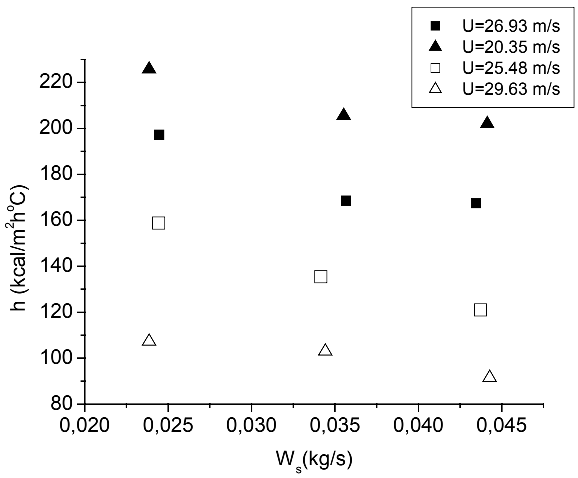


Figure 6. Gas-solid heat transfer coefficient versus solids flow rate, for glass spheres and aluminum particles, in different air velocities.

Comparisons among the results obtained for h, analyzing the effect of the morphology of particle (porous and non porous) in several solid flow rates and air velocities are shown in Tab. (3). Analyzing the experimental data and considering similar values for Ws and U, most of the results, the glass spheres presented higher values for h.

Table 3. Comparison among the results obtained for h: analysis the effect of the morphology of particle.

operational conditions		glass spheres	aluminum particles
		h (kcal/m^{2}h^{o}C)	
W_s = 0.04371 kg/s	U=29.47 m/s	131.32	91.44
	U=25.35 m/s	163.44	120.96
	U=22.38 m/s	191.52	129.60
W_s = 0.03504 kg/s	U=22.49 m/s	200.88	156.96
	U=19.53 m/s	161.76	175.32
W_s = 0.02450 kg/s	U=27.51 m/s	197.28	132.84
	U=21.62 m/s	237.60	178.56

3.3 – Sensitivity analysis on the model (Eq.(2) and (3))

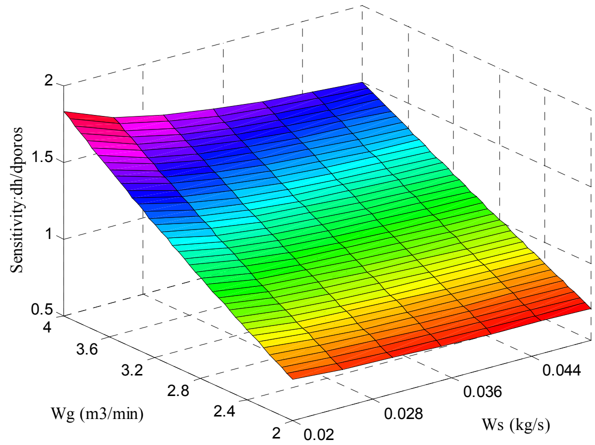
In this research, the gas-solid heat transfer, h, it was determined through the mathematical equations, they have been already discussed in item 2. Few works in literature analyse the effects of this coefficient under some parameters, so a numerical study was carried out on the parametric sensitivity of h as functions of the air and solids flow rates and bed voidage. This analysis provides useful information about the sensitivity of the model variables on the parameters which are dependent.

Equations were numerically integrated and sensitivities obtained by the central differences approach (Freitas and Freire, 2002; Giudici, 1990):

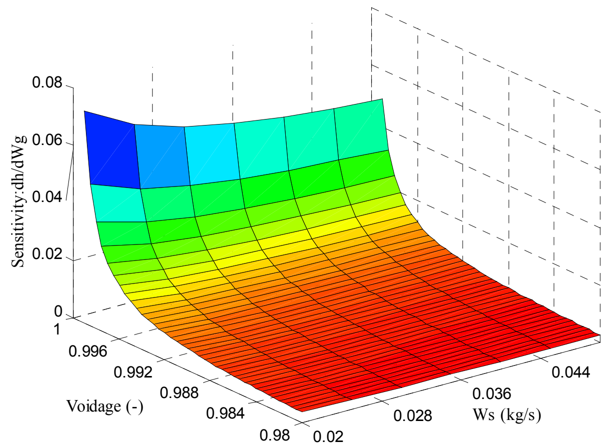
$$S_j^i = \left(\frac{\partial Y_i}{\partial b_j} \right) = \frac{Y_i(b_1,...., b_j + h_j,..., b_n) - Y_i(b_1,...b_j - h_j,..., b_n)}{2h_j} \quad (7)$$

with $h_j = 10^{-2}\, b_j$.

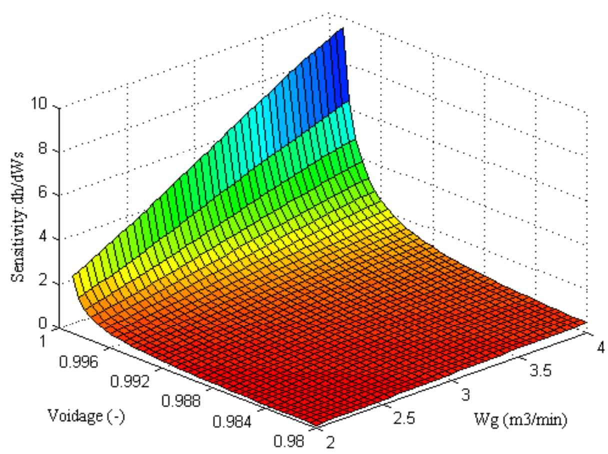
Figure (7) show the results of gas-solid heat transfer coefficient sensitivities to the voidage, solids flow rate (Ws) and volumetric air flow rate (Wg). Sensitivities are shown as surface plots for better visualization of its dependence on the analysed parameters.



(a)



(b)



(c)

Figure 7. Sensibility surfaces: (a) h parametric sensitivities to ε as functions of Wg and Ws; (b) h parametric sensitivities to Wg as functions of ε and Ws; (c) h parametric sensitivities to Ws as functions of ε and Wg.

Comparing the surfaces, it is possible to observe that the parametric sensitivity of h to Ws is the largest, with a variation in scale in the order of 10. However, in the range of experimental conditions studied ($\varepsilon<0{,}996$; $2{,}0<W_g<4{,}0$), h was almost insensible to Ws, as shown in Fig. (7-c).

Figure (7-a) the heat transfer coefficient is more signficant to voidage for the higher Wg, and for the Ws its sensibility is little accentuated. Figures (7-b) and (7-c) the air flow rate exercises larger influence on h for higher voidages and in this condition, the solids flow rate is less sensitive. Those behaviors are physically expected, once the Wg will exercise larger influence for dilute flow conditions and Ws in dense phase flows. However, as observed in Fig. (6), despite of there is a tendency, for the conditions in this work, the effect of solids flow rate on the gas-solid heat transfer is not so significant.

4. Conclusions

From the discussions showed previously, it can be concluded that:

- the experimental curves of pressure gradient versus air velocity presented a minimum pressure gradient point, wich is associated with a change in the flow regime from dense to dilute phase and those regions help in the analysis of the heat transfer behavior;
- through the experimental profiles of air temperature to gas-solid flow in pneumatic beds it was verified that the heat transfer is affected both by the solids holdup and air velocity;
- for similar operational conditions, the morphology of material (porous or non porous) did not affect significantly the experimental profiles of air temperature behavior;
- a comparison among h and the characteristic curves for the identification of the flow regimes show that h are higher in the transition between dense and dilute regimes;
- in the range of measures in this work, the effect of variation of solids flow rate on gas-solid heat transfer coefficient it was not so significant and
- the sensibility surfaces provided the knowledge of the distribuitions of sensitivity of h as functions of ε, W_s and W_g, facilitating the analyses of experimental results.

5. Acknowledgements

The authors thank the Brazilian funding agencies CNPq and PRONEX/CNPq for their financial support.

6. References

Basu, P., Nag, P.K., 1996, "Heat Transfer to Walls of a Circulating Fluidized-Bed Furnace", Chemical Engineering Science, Vol. 51, pp. 1 – 26.

Bi, H.T., Ellis, N., Abba, I.A., Grace, J.R., 2000, "A State of the Art Review of Gas-Solid Turbulent Fluidization", Chemical Engineering Science, Vol.55, pp. 4789 – 4825.

Blasco, R., Veja, R., Alvarez, P.I, 2000, "Pneumatic Drying with Superheated Steam: Bi-Dimensional Model for High Solid Concentration", Proceedings of the 12th International Drying Symposium, Edited on Cd-Rom, Netherlands.

Capes, C.E, Nakamura, K., 1973, "Vertical Pneumatic Conveying: an Experimental Study with Particles in the Intermediate and Turbulent Flow Regimes", The Canadian Journal of Chemical Engineering, Vol.51, pp. 31 – 38.

Costa, I.A., 2001, "Contribuições ao Estudo do Escoamento Sólido-Fluido nos Regimes Denso e Diluído em um Leito de Transporte Pneumático Vertical", Ph. D. Diss., Federal University of São Carlos, São Carlos, Brazil, 198 p..

Farag, I. H., Tsai, Kun-Yung, 1993, "Surface-to-Suspension Heat Transfer Model in Lean Gas-Solid Freeboard Flow", Vol. 71, The Canadian Journal of Chemical Engineering, pp. 514 – 524.

Ferreira, M.C., 1996, "Desenvolvimento de um Leito Pneumático com Alimentador Tipo Jorro", Ph. D. Diss., Federal University of São Carlos, São Carlos, Brazil, 194 p..

Freitas, L.A.P., Freire, J.T., 2002, "Sensitivity Analysis on the Fluid Dynamics of a Draft Tube Spouted Bed With Bottom Particles Feed", Drying Technology, Vol. 20, nº 6, pp. 1161 – 1175.

Giudici, R., 1990, "Modelagem de Reator de Oxidação de Etileno: Estudo de Parâmetros Térmicos e Estratégia de Diluição de Catalisador", Ph. D. Diss., São Paulo University, São Paulo, Brazil, 183 p..

Gunn, D.J., Hilal, N., 1994, "Heat Transfer from Vertical Surfaces to Dense Gas-Fluidized Beds", Int. J. Heat Mass Transfer, Vol. 37, nº 16, pp.2465 – 2473.

Hettiaratchi, K., Bradley, M.S.A, Farnish, R.J., Bridle, I., Hyder, L.M., Reed, A.R., 2000, "An Investigation Into the Effect of Product Type When Scaling for Diameter in Vertical Pipelines", Powder Technology, Vol. 112, pp. 229 – 234.

Hyder, L.M., Bradley, M.S.A., Reed, A.R., Hettiaratchi, K., 2000, "An Investigation Into Effect of Particle Size on Straight-Pipe Pressure Gradients in Lean-Phase Conveying", Powder Technology, Vol. 112, pp. 235 – 243.

Issangya, A. S., Bai, D., Bi, H. T., Lim, K. S., Zhu, J., Grace, J. R., 1999, "Suspension Densities in a High-Density Circulating Fluidized Bed Riser", Chemical Engineering Science, Vol. 54, pp. 5451 – 5460.

Lehner, P., Wirth, K.E., 1999, "Characterization of the Flow Pattern in a Downer Reactor", Chemical Engineering Science, Vol.54, pp. 5471 – 5483.

Leung, L. S., 1980, "The Ups and Downs of Gas-Solid Flow – A Review", In: Fluidization (Eds. Grace, J.R., Matsen, J. M.), New York, Plenum Press, pp. 25 – 68.

Littman, H., Morgan Iii, M.H., Paccione, J.D., Jonanovic, S.Dj., Grbavcic, Z.B., 1993, "Modeling and Measurement of the Effective Drag Coefficient in Decelarating and Non-Accelerating Turbulent Gas-Solid Dilute Phase Flow of Large Particles in a Vertical Transport Pipe", Powder Technology, Vol. 77, pp. 267 – 283.

Ma, Y., Zhu, X., 2000, "Heat Transfer Between Gas-Solids Suspension and Immersed Surface in an Upflow Fluidized Bed (Riser)", Chemical Engineering Science, Vol.55, pp. 981 – 989.

Macchi, A., Bi. H.T., Legros, R., Chaouki, J., 1999, "An Investigation of Heat Transfer From a Vertical Tube in a Spouted Bed", The Canadian Journal Of Chemical Engineering, Vol. 77, pp. 45 – 53.

Marcus, R.D., Leung, L.S., Klinzing, G.E., Risk, F., 1990, "Pneumatic Conveying of Solids: A Theoretical and Practical Approach", 1 Ed. Great Britain, St Edmundsbury Press, 575 p., (Powder Technology Series).
Massarani, G., 1997, Fluidodinâmica Em Sistemas Particulados, 1. Ed. Rio de Janeiro, RJ, Ed. UFRJ, 192 p.
Mastellone, M. L., Arena, U., 1999, "The Effect of Particle Size and Density on Solids Distribution Along the Riser of a Circulating Fluidized Bed", Chemical Engineering Science, Vol. 54, pp. 5383 – 5391.
Narimatsu, C. P., Ferreira, M. C., 2001, "Vertical Pneumatic Conveying in Dilute and Dense-Phase Flows: Experimental Study of the Influence of Particle Density and Diameter on Fluid Dynamic Behavior", Vol. 18, n^{o} 3, pp. 221 – 232.
Narimatsu, C. P., Corrêa, R. G., Freire, J. T., 2002, "Estudo Da Secagem de Partículas Porosas em Leito Pneumático Vertical: Análise Preliminar Fluidodinâmica e Térmica", Proceedings of 30th Brazilian Congress of Particulate System, Edited on Cd-Rom, Federal University of São Carlos, São Carlos, Brazil.
Ravi Sankar, S., Smith, T.N., 1986, "Slip Velocities in Pneumatic Transport – Part I", Powder Technology, Vol. 47, pp. 167 – 177.
Rocha, S.C.S., Paixão, A.E.A., 1997, "Pseudo Two-Dimensional Model for a Pneumatic Dryer", Drying Technology, Vol. 15, n^{o} 6-8, pp. 1721 – 1730.
Silva, E. M. V., Ferreira, M. C., Freire, J. T., 1996, "Mean Voidage Measurementes and Fluid Dynamic Analysis in a Circulating Fluidized Bed with Spouted Bed Type Solid Feeding System", Proceedings of 2nd European Thermal Sciences Conference and 14th UIT National Heat Transfer Conference, Edizioni ETS, Rome-Italy, pp. 1535 – 1544.
Sundaresan, R., Kolar, A. K., 2002, "Core Heat Transfer Studies in a Circulating Fluidized Bed", Powder Technology, Vol. 124, pp. 138 – 151.
Wirth, K.E., 1995, "Heat transfer in circulating fluidized beds", Chemical Engineering Science, Vol.50, n^{0} 13, p. 2137 – 2151.