Prediction of Minimum Spout Velocity and Moisture Distribution of Ammonium Perchlorate Particles in a Spouted Bed Dryer

Kalbasi, Mansour*+***; Bahramian, Ali Reza; Khorshidi, Jamshid***

Department of Chemical Engineering, Amirkabir University of Technology,
P.O. Box 15875-4413 Tehran, I.R. IRAN

ABSTRACT: *Ammonium perchlorate particles have been dried in a laboratory spouted bed dryer (screen-bottomed type) which is categorized as a fluidized bed dryer. The solid particles obtained in this process of drying were semi-porous and known as the group D of Geldart classification. The variations of moisture content with resident time, the effects of bed height on the pressure drop, and the influence of moisture content on drying rate were investigated. In this project, the air flow rate and the moisture diffusivity were determined. A model to determine the minimum spout velocity and also a model based on the Fick's law were obtained which predicted the experimental data very well.*

KEY WORDS: *Drying, Spouted bed, Ammonium perchlorate, Minimum spout velocity, Moisture.*

INTRODUCTION

Spouted bed dryer is a kind of fluidized bed dryer and due to its high heat and mass transfer rates, it has industrial applications. It is mainly used for drying sticky and dense materials which are not easy to fluidize.

Mathur and *Gishler* [1] investigated the effects of column diameter, bed depth and physical properties of solids and fluids on spouting behavior. They also correlated a minimum fluid velocity for spouting empirically for wheat as follows:

$$u_{ms} = \left(\frac{d_p}{d_c}\right)\left(\frac{d_i}{d_c}\right)^{1/3}\left[\frac{2g\Delta H_v\left(\rho_s-\rho_g\right)}{\rho_g}\right]^{1/2} \qquad (1)$$

Literature reviews by *Mathur* and *Epstein* [2] reveal hydrodynamics and heat transfer studies in spouted beds. *Kmiec* [3] introduced an equation for a maximum pressure drop in a spouted bed as follows :

$$\Delta P_m = \Delta P_g\left[1+0.206\exp\left(0.62\frac{H_\circ}{r_c}\right)\right] \qquad (2)$$

where : $\Delta P_g = g(1-\varepsilon)(\rho_s-\rho_g)H_\circ$

The author reported that the maximum pressure drop for the spouted bed was 1-2 times higher than the pressure drop for a fluidized bed . Microwave drying of ammonium perchlorate has been investigated for

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* *To whom correspondence should be addressed.*

\+ *E-mail: mkalbsi@aut.ac.ir*

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grinding spheres by *Sayles* and *Ala* [4]. They reported an energy saving of 40-50 % compared to a conventional hot air dryer.

Olazar et al. [6] studied the pressure drop for conical spouted beds and derived an equation as follows :

$$-\frac{\Delta P_s}{H_\circ \rho_s g} = 1.20\left[\tan\left(\frac{\gamma}{2}\right)\right]^{-0.11} \mathrm{Re}^{-0.06}\left(\frac{H_\circ}{d_i}\right)^{0.08} \qquad (3)$$

They also studied the pressure drop for jet spouted bed as functions of angle, bed height, and fluid inlet diameter.

Since the rates of heat and mass transfer determines the overall drying rate in the falling rate period, drying time will increase slightly if convective heat and mass transfer is not supplied at high intensity continuously.

Therefore, *Mujumdar* [5] provided supplying spouting air periodically for particulate materials drying in falling rate period to save air consumption and thermal energy. Rotating jet annular spouted bed dryer was developed for drying of wheat, corn, and polystyrene particulates in the falling rate period to save air consumption and thermal energy. A rotating jet annular spouted bed dryer was developed for drying of wheat, corn and polystyrene particulates in the falling rate period by *Devahastin*, *Mujumdar* and *Raghavan* [7]. Their observations were used to define a fictitious column diameter to calculate the nozzle minimum spouting velocity. They introduced an equation to base the minimum spouting velocity on the nozzle diameter rather than the column diameter as follows:

$$d_{cf} = 156.36\frac{d_p^{1.223}}{d_n^{0.223} \cdot u_{msn}^{1.170}}\left[\frac{2gH_\circ(\rho_s-\rho_g)}{\rho_g}\right]^{0.585} \qquad (4)$$

Wang and *Chen* [8] recognized that three basic mechanisms of moisture transport existed in the moist porous media as capillary flow , vapour diffusion and evaporation-condensation. *Wang* and *Chen* [10] have also analyzed the heat and mass transfer mechanisms in the fluidized - bed drying process of apple. They introduced a parameter called a bed area factor which reflected the number of particle hold - up per cross - sectional area of fluidized -bed. They observed that an increase in the bed area factor would result in an increase in the relative humidity value of the exhaust air. A mathematical model for a batch fluidized bed dryer presented by *Mola* and *Montazeri* [9]. The moisture content and temperature of wheat particles and air were given as follow:

$$\varepsilon\rho_g u_g(1+y).c_{p_g}\frac{dT_g}{dz} - \qquad (5)$$

$$\left[c_{p_g}+(1+y)c_{p_v}\right]\dot{m}T_g - Ah_c(T_g-T_s)=0$$

$$(1-\varepsilon)\cdot\rho_s(1+X)\cdot c_{Ps}\frac{dT_s}{dt} - \left[c_{Ps}+(1+X)c_{Pw}\right]mT_s + \qquad (6)$$

$$\dot{m}\Delta H_v - Ah_c(T_g-T_s)=0$$

They obtained these equations by writing differential mass and energy balances for gas and solids phases over a differential control volume.

Hattori et al. [12] have concluded that within the three groups of spouted bed dryers namely, draft - tube , screen - bottomed and top - sealed, the screen - bottomed has the most capability of drying the materials whilst the draft - tube has the least drying rate.

Wang et al. [13] introduced auxiliary gas in a spouted bed horizontally and investigated its effects on minimum spouted velocity and fountain height without fluidization of annulus. They proposed a model as follows:

$$\frac{\varepsilon}{1-\varepsilon}\cdot\frac{d_p \cdot u_{ms}}{\mu_g} = 0.25\left(\frac{H_o}{d_c}\right)^{0.38} \times \left(\frac{d_p}{d_c}\right)^{2.54} \times \qquad (7)$$

$$\left(\frac{d_i}{d_c}\right)^{0.33}\left[\frac{\rho_g(\rho_s-\rho_g)gd_c^3}{\mu_g^2}\right]^{0.75} \mathrm{Re}_a^{-0.6}$$

where: $13 \le \mathrm{Re}_a \le 82$

Davidson et al. [14] studied the rate of evaporation of water from air - fluidized bed of silica - alumina cracking catalyst. They measured the drying rate as a function of water content and concluded that the transition point between the constant and the falling rates represented the monolayer coverage. They added that the falling rate period was caused by progressive depletion of the monolayer and a second - order drying law was appropriate to describe the falling - rate drying for small micro - porous particles.

EXPERIMENTAL WORK

The apparatus used in this project was a laboratory plexiglass spouted bed (screen-bottomed type) model

STREA-1 with a perforated plate as an air distributor (standard 60 mesh) at the bottom (Fig. 1). The dryer had a cylindrical part with 0.25 m diameter and 0.18 m height and a conical part with 0.30 m height and angle of 24°.

The dryer inlet air diameter was 0.12 m and the outlet air diameter was 0.08 m. The required air for the dryer was supplied by a compressor of 4 to 6 bar pressure (1) and after the air dehumidification, its pressure adjusted to a required amount and reached the apparatus through a half an inch pipe. A pipe (6) passed through a mesh under the dryer caused movement of the particles at the center (spout region) and two pipes annular region (5) caused the circulation of the particles at the annular region (annulus region) .

The adjustable rotameter (3) measure the inlet air flow to the dryer in cubic meter per hour.

The manometer (10) shows the product resistance of the screen-bottomed. Since the product resistance remain constant, when the bed height remains constant, the bed pressure drop may be considered.

The manometer (11) shows the outlet air filter resistance. This filter indicates the amount of the filter dirt. The air heated by electric element (4) enter the dryer through a pipe (6). The prob thermometer (12) measures the air temperature.

The apparatus had four high temperature resistance bag filters to prevent the particles larger than 2 μm exiting from the dryer. The humid air exited from the dryer top through a 3m pipe.

A high precision digital balance (Mettler type) was used to measure the variations of product weight at certain time intervals. The air passed through the distributor, traveled through the ammonium perchlorate particles bed upwards and at the top of the bed, the particles separated from the air and fell in the downcomer region. The air then entered a cylindrical part of the dryer while reducing in velocity. In the center, the particles traveled upwards co-currently with the air flow in the light phase (spout region).

The particles then traveled counter-current near the dryer wall downwards in the dense phase (annulus region). Combination of these two hydrodynamic region led to more heat and mass transfer and moisture transfer rate.

RESULTS AND DISCUSSION

In this project various experimental drying curves were obtained. Variation of particle moisture content with drying time shown in Fig. 2 for different temperatures was obtained experimentally in the present work (similar trends were observed in the previous study on drying of potato), according to *Kalbasi*, *Mehraban* [11], and also on drying of onion by *Kalbasi* [15]. Variation of drying rate with moisture content for different temperatures are shown in Fig. 3 which was obtained experimentally in the present work.

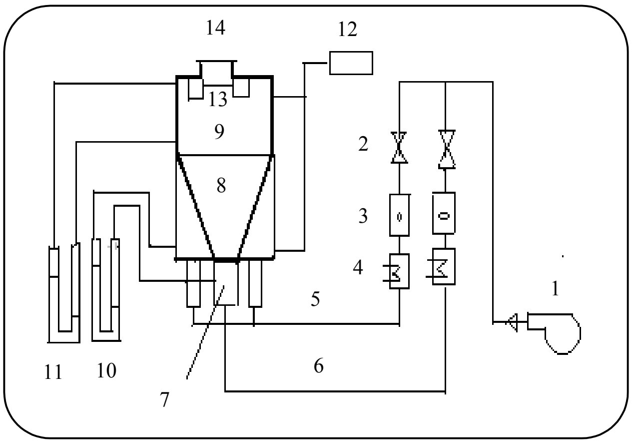

***Fig. 1:** Schematic diagram of experimental apparatus (1-Air compressor, 2-Valve, 3-Rotameter, 4-Electrical element, 5- Auxiliary gas, 6- Spout gas, 7- Nozzle, 8- Conical section, 9- Cylindrical section, 10 - Manometer, 11- Manometer, 12- Prob thermometer, 13-Filter, 14- Outlet air).*

As is observed in Fig. 3, a point in the curve where the slope of the drying curve changes from constant rate to falling rate, is called the critical moisture (X_{cr}). when $X<X_{cr}$ the amount of the moisture that reaches the surface from inside of the material , starts to decrease gradually and as a result, the vapour pressure over the material surface reduces and causes the drying rate to decrease. This state corresponds to the drying falling rate period. When $X>X_{cr}$ the amount of heat transferred from the air to the particle surface becomes equal to the amount of heat required to evaporates the moisture and this state is known as the constant rate period. The application of these two curves in determining the moisture diffusivity explains further.

In this work, the minimum spout velocity is measured by observation. The point where the spout collapses and the bed pressure drop increases suddenly (Fig. 6) while the gas velocity is reduced corresponds to the minimum spout velocity.

According to three important parameters in determination of the minimum spout velocity in our

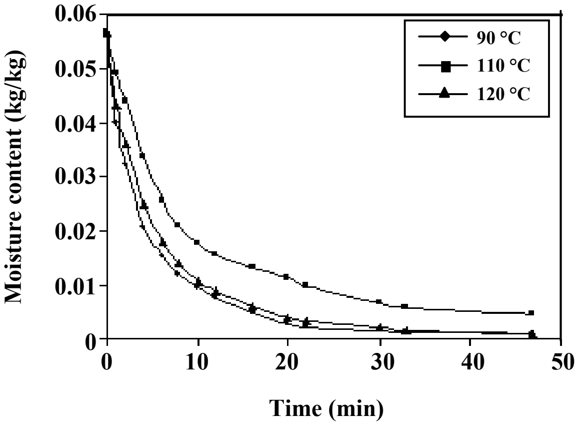

Fig. 2: Moisture content vs. time for different temperatures.

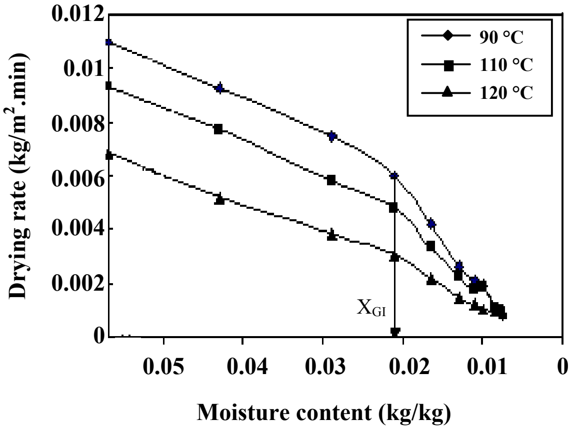

Fig. 3: Drying rate vs. Moisture content for different temperatures.

experiments the general form of the equation is as follow:

$$\mathrm{Re}_{ms} = a\left(\frac{H_\circ}{d_c}\right)^{b} .\mathrm{Ar}^{c} .\mathrm{Re}^{d} \qquad (8)$$

The coefficients a, b, c and d in the above equations are constants and were found experimentally. Considering three important parameters in determination of the minimum spout velocity bed height of ammonium perchlorate particles, its effect on *Archimedes* number as a dimensionless parameter, also the effect of the apparent air flow rate and its effects on the dimensionless *Reynolds* number, and the various particles beds and dividing it on the dryer inlet, the diameters were made dimensionless.

By proceeding various experiments on various bed heights, variety of inlet air, and particles mean diameters, the coefficients a, b, c and d were determined. On this basis, a semi-empirical equation which is able to explain this systems characterizations such as the minimum spout velocity for the ammonium perchlorate crystal particles, was determined. The results of the minimum spout velocity of ammonium perchlorate particles in the present experimental are displayed in table 1. The values calculated by equation (7) (with auxiliary gas) and our experimental work are also listed.

Concerning the basic three parameters responsible for the total minimum spout velocity U_{mt} which is written as $U_{mt}=U_{ms}+U_a$, in which U_{ms} is a minimum spout velocity and U_a is an apparent gas spout velocity.

The effects of the bed height, particle diameter and the auxiliary gas apparent velocity on the experimental data were investigated.

It is observed from (Fig. 4) that the minimum spout velocity increases by the bed height and particle diameter increase (with no auxiliary gas). Therefore, the slope of the curve 4 is positive. Fig. 4 indicates the effects of static bed depth on minimum spout velocity for different particle diameters. As shown, increasing the bed depth causes enhancement in the minimum spout velocity and this is more pronounced as the particle diameters increase. Although the experimental data in Fig. 4 are not completely linear but to obtain the slope of the lines (in equation (8)) the data were assumed to be linear. The effects of inlet gas velocity on minimum spout velocity are shown in Fig. 5 for different bed heights. As observed, the increase in the inlet air velocity causes reduction in the minimum spout velocity and this effect is more pronounced as the bed height decreases.

Fig. 5 indicates that the total spouted velocity decreases as the auxiliary gas velocity increases. Therefore, U_a enhancement causes the flow circulation regime annular region of the bed and decreases the total spout velocity. Therefore, the curve slope is negative.

The slope of the curves 4 and 5 will be the constant of the following relationship which indicate the effect of each mentioned parameters on the basic of the experimental data.

According to slope of the curves 4 and 5 and U_{ms} experimental values of Table1 the coefficients a ,b, c and d in equation (8), were determined.

Therefore, equation (8) takes the following form:

$$\mathrm{Re}_{ms} = 0.5\left(H_\circ/d_c\right)^{0.673} .\mathrm{Ar}^{0.762} .\mathrm{Re}_a^{-0.963} \qquad (9)$$

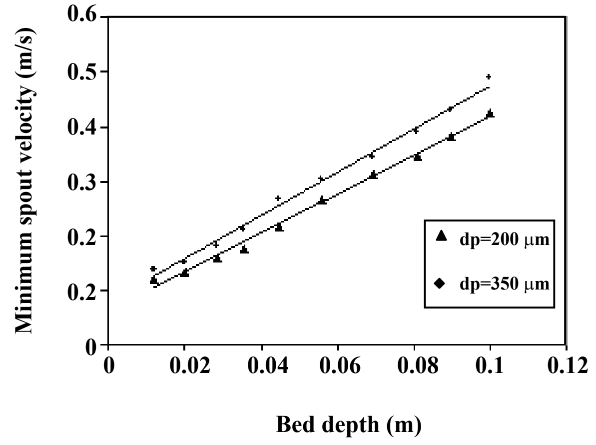

Fig. 4: Minimum spout velocity vs. bed depth for different particle diameter (without auxiliary gas).

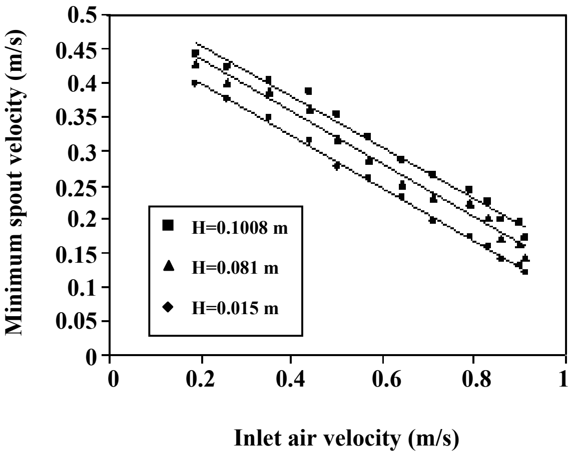

Fig. 5: Minimum spout velocity vs. inlet auxiliary air velocity for different bed heights.

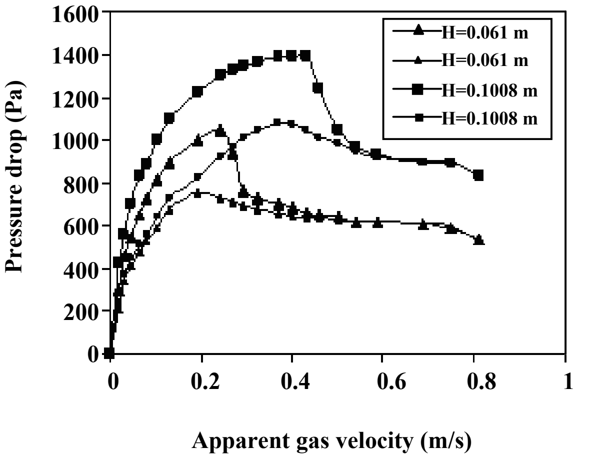

Fig. 6: Pressure drop vs. apparent gas spout velocity for different bed heights.

where:

$$Ar = \frac{g . d_p^3 . \rho_g \left(\rho_s - \rho_g\right)}{\mu^2{}_g} \tag{10}$$

$$Re_{ms} = \frac{\rho_g . u_{ms} . d_p}{\mu_g} . \frac{\varepsilon}{1-\varepsilon} \tag{11}$$

$$Re_a = \frac{\rho_g . u_a . d_p}{\mu_g} \tag{12}$$

The constants in the equation (8) determined by least square fitting of the experimental data. The operating conditions were:

$\frac{d_i}{d_c} = 0.5$, $\gamma = 24^\circ$, $200\,\mu m \le d_p \le 350\,\mu m$

$0.015\,m \le H_\circ \le 0.100\,m$

The mean standard deviation was found to be 17 %.

In equation of Re_{ms}, ε is fraction void of ammonium perchlorate particle and measured by values of density.

The results of the experimental data for densities and porosities of ammonium perchlorate particles are displayed in tables 2, 3 and 4.

In table 4, weight of unit mass, i.e., division of mass over particle volume is called bed density (ρ_b). ρ_s is mass of packed material obtained by pychnometry is known as the solid density. And ρ_p particle density with voidage between them which is obtained from reference [16] is called particle density.

Also ε_p and ε_o refering to particle voidage, and total voidage respectively, are calculated by follow :

where: $\varepsilon_p = 1 - \frac{\rho_p}{\rho_s}$ and , $\varepsilon_\circ = 1 - \frac{\rho_b}{\rho_s}$

The difference between total particle and particle void is called void fraction (ε).

$$\varepsilon = \varepsilon_o - \varepsilon_p$$

Variations of pressure drop with gas spout velocity are shown in Fig. 6 for different bed heights. (solid curves refers to increasing and dashed curves refers to decreasing apparent gas velocity).

As shown, increasing the apparent gas velocity causes the pressure drop in the bed to increase initially until the

Table 1: Comparison of Experimental Data and Calculated value for U_{ms}.

Material	H_o (m)	U_a (m/s)	U_{ms} (exp) (m/s)	U_{ms} (m/s)	
				Eq 8	Eq 7
Ammonium perchlorate	0.015	0.00	0.47	0.402	0.388
	0.015	0.294	0.41	0.385	0.305
	0.015	0.490	0.347	0.242	0.224
	0.015	0.60	0.225	0.207	0.203
	0.061	0.00	0.55	0.491	0.487
	0.061	0.290	0.541	0.460	0.436
	0.061	0.490	0.400	0.363	0.342
	0.061	0.61	0.298	0.400	0.389
	0.101	0.00	0.621	0.580	0.557
	0.101	0.291	0.582	0.493	0.487
	0.101	0.493	0.441	0.370	0.342
	0.101	0.61	0.396	0.396	0.300

particles within the bed reach the minimum spout velocity. At this time the pressure suddenly reduces and finally the bed pressure reaches an equilibrium with the bed weight and at this time , increasing the gas velocity enhances the drag force on the particle.

In this work, a model based on the following assumptions was developed to determine the mean moisture content of the particles:

1- The particles are assumed to be spherical.

2- Evaporation takes place from the surface of the material.

3- The heat and mass transfer in the gas phase assumed negligible.

The moisture transferare are assumed to be uni-directional cone diameter molecular diffusion

Therefore, by using the fick's law , one obtains:

$$\frac{\overline{X}(r,t)-X_e}{X(0,t)-X_e}=\frac{6}{\pi^2}\exp\left(\frac{-\pi^2.D.t}{R^2}\right) \qquad (13)$$

The general model in determining the moisture is as:

$$\frac{\overline{X}(r,t)-X_e}{X(0,t)-X_e}=\sum_{n=0}^{\infty}\frac{6}{\pi^2}\exp\left(\frac{-n^2\pi^2 Dt}{R^2}\right) \qquad (14)$$

Considering the moisture determination of the ammonium perchlorate particles at each moment, the initial and final moisture content were determined from experimental data in this project. X(r,t) was the particles moisture content at different times which was measured by material sampling from the dryer at different times. The apparatus for this purpose was *Karl-Fischer* humidity gauge model Mettler, D18. The results obtained by this apparatus are available in Fig. 2.

$X(r_o,t)$ was the particles initial moisture content and was measured by putting a known amount of particles in the electron moisture balance at 100 °C in adequate time until the particle weight remains unchanged. X_e was the equilibrium moisture content of the particles and was measured by contacting a known amount of ammonium perchlorate crystals with humid air for an adequate time so that the particle moisture content remains constant. The experimental value was X_e=0.0568 kg/kg.

It was observed that the amount of fraction at the left hand of the above relationship give good result for n=1 . Therefore, only the first term (n=1) of equation (11) for calculation of the ammonium perchlorate particles average moisture content has been found adequate and for n>1 , the precision of the calculation decrease.

The variations of moisture diffusivity with moisture content determined by this equation is shown in Fig. 7.

Fig. 7 was obtained on the basis of the experimental data of Fig. 2 and equation (10).

Also by having the particles mean diameters one can measure R (the particle mean radius), and by passing the particles through the different mesh having international standard ISO565 and Fig. 2 which shows the particles moisture content as a function of particles residence time in the dryer, one can obtain the diffusion coefficient of the ammonium perchlorate particles from equation (9).

As is observed from the Fig. 7, the inlet air temperature enhancement, increase the moisture diffusivity. As indicated from Figs. 2 and 3, the particle drying is divided into two parts. On the basis of Fig. 2, the particle moisture decreases by time.

This is the falling rate period for which one may conclude as in Fig. 7, that the moisture diffusivity of the ammonium perchlorate crystals first show a partial increase (which belongs to the first drying period) and then a decrease in ammonium cotent.

Table 2: Experimental data for particle mass variations with bed height and bed volume for Ammonium perchlorate.

Particle mass (gr)	Bed Height (m)	Bed volume (cm^3)
20	0.015	97
60	0.042	218
100	0.069	396
120	0.081	481
160	0.101	640

Table 3: Particle mass variation with densities for Ammonium perchlorate.

Particle mass (gr)	Bed Height (m)	Bed volume (cm^3)
20	0.015	97
60	0.042	218
100	0.069	396
120	0.081	481
160	0.101	640

Table 4: Particle mass variation with porosities for Ammonium perchlorate.

Mass (gr)	ε_p (cm^3/cm^3)	ε_o (cm^3/cm^3)	ε (cm^3/cm^3)
20	0.214	0.887	0.673
60	0.214	0.889	0.675
100	0.214	0.898	0.684
120	0.214	0.899	0.685
160	0.214	0.899	0.685

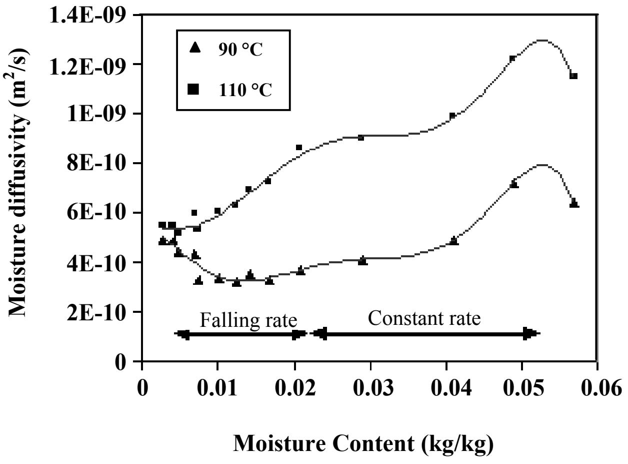

Fig. 7: Moisture diffusivity vs. moisture content at two temperatures.

CONCLUSIONS

In this project, a semi-empirical correlation for determination of the minimum spout velocity was obtained. for this purpose, the effect of three effective parameters on spout velocity such as bed height, particle diameters and auxiliary inlet gas air velocity, were investigated. The coefficients of each parameter were determined according to the data obtained experimentally, according to equation (8), two parameters such as bed height and particle diameters were shown to have straight relationship with the minimum spout velocity. But the auxiliary gas velocity showed negative relationship with the minimum spout velocity. Moreover, the ammonium perchlorate of critical and equilibrium moisture content of ammonium perchlorate crystal particles and their porosities were determined experimentally and on the basis of the fick's diffusion equation, the diffusivity of ammonium perchlorate particles was obtained.

Nomenclatures

A	Particle specific surface (m^2/m^3)
C_P	Heat capacity (g: gas , s: solid , v: vapour , w: water) (kj/kg.k)
D	Moisture diffusion coefficient (m^2/s)
d	Diameter (c: column , cf: fictitious column, i: gas inlet , n: nuzzle , p: particle) (m)
g	Acceleration due to gravity (m/s^2)
H_o	Static bed height (m)
ΔH_V	Latent heat of vaporization (kj/kg)
h_C	Convective heat transfer coefficient (w/m^2k)
$\dot{m}$	Evaporation rate (kg/m^2s)
N	Drying rate (kg/m^2.min)
ΔP	Pressure drop (g: gas, m: maximum spouted bed, s: spouted bed) (pa)
R	Particle radius (μm)
r	Radial distance from center of the particle (μm)
r_c	Column cylindrical radius (m)
T	Temperature (k)
t	Time (min)
u	Velocity (a:apparent gas, g: gas, ms: minimum spouting , msn: nuzzle minimum spouting) (m/s)
U_{mt}	Total minimum spout velocity
X	Particle moisture content (e: equilibrium, -: mean) (kg/kg)

y	Air humidity (kg/kg)
ρ	Density (g: gas , s: solid) (kg/m^3)
μ_g	Dynamic gas viscosity (kg/m.s)
γ	Cone angle (degree)
Δ	Difference
ε	Bed voidage

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REFERENCES

[1] Mathur, K.B. and Gishler, P.E., A technique for contact gases with coarse solid particles, *AIChE J.*, **1**, 157 (1955).

[2] Mathur, K.B. and Epstein, N., "Spouted Beds", Academic press,New York (1974).

[3] Kmiec, A., Hydrodynamics of flows and heat transfer in spouted beds, *Chem. Eng. J.*, **19**, 189 (1980).

[4] Sayles, D.C. and Ala, H., Microwave drying of ammonium perchlorate grinding spheres, US patent, **4**, 513 (1985).

[5] Mujumdar, A.S., Recent developments in spouted bed drying, keynote lecture, Transport Process in Porous Media Conference, Saocarlos. S.P., Brazil, (1989)

[6] Olazar, M., San jose, M.J., Aguayo, A.T., Arandes J.M., Pressure drop in conical spouted beds, *Chem. Eng. J.*, **51**, 53 (1995).

[7] Davahastin, S., Mujumdar, and Raghavan, G.S., Hydrodynamic characteristics of a rotary jet annular spouted bed, *J. Powder Technology*, **103**, 169 (1999).

[8] Wang, Z.H. and Chen, G., Heat and mass trasfer during low intensity convective drying, *Chem. Eng. Sci.*, **54**, 3899 (1999).

[9] Mola, D. and Montazeri, H., Evaporation condensation and coagulation processes, *J. Aerosol Sci.*, **31**, 5793 (2000).

[10] Wang, Z.H. and Chen, G., Heat and mass trasfer in batch fluidized bed drying of porous particles, *Chem. Eng. Sci.*, **55**, 1857 (2000).

[11] Kalbasi, M., Mehraban, M.R., The effect of surface water vapour flux on drying of potato, *Trans IChem. Eng.*, **78**, 204 (2000).

[12] Hattori, H., Morimoto, T., Yamaguchi, M., Onez-awa, T. and Avac, C., Drying of porous solid particles in various-shaped spouted bed with a draft-tube, *J. Chem. Eng. of Japan*, **34**, 1549 (2001).

[13] Wang, Z., Chen, P., Li, H., Wu. C. and Chen,Y., Study on the hydrodynamics of a spouting-moving bed, *Ind. Eng. Chem. Res.*, **40**, 4983 (2001).

[14] Davidson, J. F., Thorpe, R. B., Al-Mansouri, O., Kwaong, H., Peck, M. and Williamson, R., Evaporation of water from air-fluidized porous particles, *Chem. Eng. Sci.*, **56**, 6089 (2001).

[15] Kalbasi, M., Heat and moisture transfer model for onion drying, *Drying Technology*, **21**, 1575 (2003)

[16] Perry, R.H. and W .Green, D., "Perry's Chemical Engineers Handbook", 5th Ed., McGrow-Hill Book Company, New York (1997).