UNIVERSITY OF NIŠ
The scientific journal **FACTA UNIVERSITATIS**
Series: **Mechanical Engineering** Vol.1, N^{o} 4, 1997 pp. 469 - 478
Editor of series: Nenad Radojković
Address: Univerzitetski trg 2, 18000 Niš, YU,
Tel: (018) 547-095, Fax: (018)-24-488

EXPERIMENTAL STUDY ON DRYING KINETICS OF SOLID PARTICLES IN FLUIDIZED BED

UDK: 536.2:66.047

Wlodzimierz Ciesielczyk*, Mladen Stojiljković, Gradimir Ilić**, Nenad Radojković**, Mića Vukić****

*Institute of Chemical Engineering and Physical Chemistry, Technical University of Cracow, Poland, **Faculty of Mechanical Engineering, Beogradska 14, 18000 Niš YU

Abstract. *Based on experimental results on kinetics of silica gel polytetrafluoroethylene, sand and ammonium sulphate drying in fluidized bed and a correlation equation for the mean gas solid heat transfer coefficient in the constant-drayng-rate period a kinetics equation is proposed for both characteristic drying periods. The suitability of introducing the shape factor of the solid particle into the kinetic equation is shown.*

INTRODUCTION

In spite of the widespread industrial application of fluidized bed dryers and a number of papers [1-6] on this topic, the aim of working out directions for dryers design has not been achieved so far. A lot of information, particularly on the kinetics of fluidized bed drying; which can be found in literature, are divergent and contradictory as shown [4].

These divergences encouraged us to undertake the research on the fluidized bed drying kinetics of selected materials with the aim of elaborating a useful kinetic equation and explaining the effect of the parameters, which either have had their influence interpreted in a different way or have been left out of account in research programmes; e.g. the shape factor of the solid particle.

LITERATURE STUDY

From the literature study of the convective fluidized bed drying of solid particles, it can be concluded that the interest of research workers is fundamentally concerned with:

- becoming acquainted with the mechanism of the processes, occurring inside the

---

Received, April 4, 1997

drying particle and on the surface,
- working out mathematical models and correlation equations needed for design.

These problems are connected with the process kinetics, expressing the relationship between the rate of drying, the structure of the solid particle and the condition at which the process occurs.

The proposed analytical correlation, obtained from several theories [2-6], cannot be used in design, mainly because of the lack of coefficients characterizing momentum, heat and mass transfer for various materials, used in industry.

In this case, in parallel with theoretical study advancement of semi-empirical methods, based on the simple models of drying kinetics and experimental results, was carried out. On the assumption [2] for the first drying period, described by the kinetic Equation (1),

$$-\left(\frac{d\omega}{d\tau}\right)_{\mathrm{I}} = N \qquad \omega_1 \geq \omega \geq \omega_{cr} \tag{1}$$

the heat transferred into a spherical particle is used for vaporizing water (the vaporization occurs on the outside surface of the particle, covered by water) and that the particle temperature is equal to the wet bulb temperature, the first drying period can be described by the following heat transfer equation:

$$m_s \cdot N \cdot r = \alpha \cdot a \cdot V_0 \cdot \Delta T_m \tag{2}$$

where:

$$a = \frac{6(1-\varepsilon_0)\Phi}{d_s} \tag{3}$$

$$\varepsilon_0 = \frac{\rho_u}{\rho_s} \tag{4}$$

$$\rho_u = \frac{m_s}{V_0} \tag{5}$$

$$\Delta T_m = \frac{T_{g1} - T_{g2}}{\left(\dfrac{T_{g1} - T_{ms}}{T_{g2} - T_{ms}}\right)} \tag{6}$$

From Equations (2), (4) and (5) the rate of drying in the first period can be calculated as:

$$N = \frac{6 \cdot \alpha \cdot \Delta T_m \cdot \Phi}{r \cdot d_s \cdot \rho_s} \tag{7}$$

The mean transfer coefficient from the gas to the solid particle a can be estimated from criteria equations (Table 1). However, the published criteria equations that permit the determination of the mean gas-solid heat transfer coefficient for the first constant-rate period show divergences.

According to [3] these divergences are largely due to:
- not rigorously estimating the interfacial area (without taking into consideration the real shape of the solid particle),

– different methods used for calculating the process driving force ΔT_m (the gas and solid particle temperatures not precisely measured),

– different hydrodynamic conditions prevailing during experiments.

Table 1. The correlation equations for the gas - solid heat transfer coefficient in the first constant – drying rate period of fluidized bed drying

No	Author	Range of dimensionless number	Equation	Notes
1	Fiedorov [7]	$2\cdot10^3<Ar<7.5\cdot10^5$	$Nu=1.63\cdot10^{-2}Ar^{0.246}Rc^{0.65}\left(\frac{H_0}{d_s}\right)^{-0.32}$	
1’		$7.5\cdot10^5<Ar<6\cdot10^5$	$Nu=3.02\cdot10^{-2}Ar^{0.201}Re^{0.65}\left(\frac{H_0}{d_s}\right)^{-0.34}$	
1”		$20<Re<500$	$Nu=2.3\cdot10^{-1}Re^{0.363}$	
2	Kettenring Manderfield [8]	$9<Re<55$	$Nu=1.35\cdot10^{-2}Re^{1.30}$	
3	Heertjes McKibbins [9]	$8.8<Re<52.3$	$\alpha=7.426Re^{0.76}$	
3’		$4\cdot10^{-3}<\frac{d_s}{D_K}<24\cdot1$ $9<Re<74$	$Nu=C\varepsilon_0^3Fr^{-0.49}Re^{0.97}\left(\frac{d_e}{D_K}\right)^{0.17}Pr^{0.33}$	C-constant
4	Shi-Jan-Fou Romankov [10] Rashkovskaya	$5.5<Re<280$ $7.85<\frac{H_M}{d_s}<130$ $0.02<\frac{P_p}{P_g}<0{,}12$	$Nu=2.5\cdot10^{-1}Re\left(\frac{H_M}{d_s}\right)^{-1}$	$H_M=H_0(1-\varepsilon_0)$
4’			$Nu=8\cdot10^{-1}Re\left(\frac{H_M}{d_s}\right)^{-1}\left(\frac{P_p}{P_g}\right)^{0.25}$	
5	Kunii Levenspiel [12]		$Nu=3\cdot10^{-2}Re^{1.3}$	
6	Walton, Olson [13]	$6<Re<50$	$Nu=2.8\cdot10^{-3}Re^{1.7}\left(\frac{D_K}{d_s}\right)^{0.2}$	
7	Mlodziński [3]	$5<Re<30$	$Nu=2.36\cdot10^{-2}Re^{1.1}$	
8	Lykov [14]		$Nu=1.6\cdot10^{-3}\left(\frac{Re}{\varepsilon_0}\right)^{0.35}\left(\frac{u_g}{u_{gw}}\right)^{-1.5}$	U_{gw}-maximum fluidization velocity
8’			$Nu=8.7\cdot10^{-3}Re^{0.84}$	
9	Zabrodsky [11]		$Nu=1.25\cdot10^{-3}Re^{1.46}$	
10	Gamson [1]	$Re_M<10$	$St=\frac{Nu}{Re\cdot Pr}=1.83Pr^{-0.66}Re_M^{-1}(1-\varepsilon_0)^{0.2}$	$Re_M=\frac{Re}{1-\varepsilon_0}$
10’		$10<Re_M<100$	$St=Pr^{-0.66}f\left[\frac{Re_M}{1-\varepsilon_0}\right]$	
10”		$Re_M>100$	$St=1.57Pr^{-0.66}Re_M^{-0.11}(1-\varepsilon_0)^{0.2}$	
11	Ju-Chin-Chu [14]	$Re_M<30$	$Nu=3.46Re^{0.22}(1-\varepsilon_0)^{0.78}$	
11’		$Re_M>30$	$Nu=1.07Re^{0.56}(1-\varepsilon_0)^{0.44}$	

12	Frantz [15]	8<*Re*<80	$Nu = 1.5 \cdot 10^{-2} Re^{1.6} Pr^{0.67}$	Thermocouple with the shield
12’			$Nu = 1.6 \cdot 10^{-2} Re^{1.3} Pr^{0.67}$	Thermocouple without the shield
13	Leva [12]	8<*Re*<100	$Nu = 6.3 \cdot 10^{-3} Re^{1.8}$	
14	Galperin [16]	$\frac{Re}{\varepsilon_0} < 200$	$Nu = 4 \cdot 10^{-1} \left(\frac{Re}{\varepsilon_0} \right)^{1.3} Pr^{0.33}$	
14’		$\frac{Re}{\varepsilon_0} > 200$	$Nu = 4 \cdot 10^{-1} \left(\frac{Re}{\varepsilon_0} \right)^{0.66} Pr^{0.33}$	
15	Ciesielczyk Mrowiec [4]	3.61<*Re*<125 $1.24 \cdot 10^3 < Ar < 1.14 \cdot 10^5$ $121 < \frac{H_0}{d_s} < 705$ 1.14<*Φ*<1.81	$Nu = 0.106 Re Ar^{0.437} \left(\frac{H_0}{d_s} \right)^{-0.803} \Phi^{1.12}$	
16	Kmieć [17]	10<*Re*<125 $2.8 \cdot 10^3 < Ar < 1.84 \cdot 10^6$ 1.11<*Φ*<1.41 $0.268 < \mathrm{tg} \frac{\gamma}{2} < 1.00$	$Nu = 0.897 Re^{0.464} Pr^{0.333} Ar^{0.116} \left(\mathrm{tg} \frac{\gamma}{2} \right)^{-0.813} \left(\frac{H_0}{d_s} \right)^{-1.19} \Phi^{2.281}$	

In the absence of any universal correlation equation for estimating the gas-solid heat transfer coefficient α, the best data can be found on the basis of experiments on kinetics of fluidized bed drying for a given material and for given operating conditions.

Experimental results are usually shown as the plots of the moisture content of solid versus time ($\omega = \mathrm{f}(\tau)$). Thereby drying curves for a given material are obtained [1].

The drying curve for the first period is described by the following straight-line equation:

$$\omega = \omega_1 - N \cdot \tau \tag{8}$$

Finding the general kinetic equation for the falling-rate period (the second period) is much more difficult, because according to the kind of material and moisture content, the mechanism of moisture movement inside the solid particle during drying is different and comes under different physical laws. The research carried out an this problem was concentrated on finding the method of generalizing the experimental results [2, 4, 5].

Kinetic equation for the second period is described by the following relationship:

$$-\left(\frac{d\omega}{d\tau} \right)_{\mathrm{II}} = K(\omega - \omega_r) \quad \omega_1 \le \omega_{cr} \tag{9}$$

The drying coefficient K can be related [4] to the maximum drying rate:

$$K = \%N = \frac{1}{\omega_{cr} - \omega_r} N \tag{10}$$

On the assumption that for the second period the relationship lg(w-w_r)=f($=N \cdot \tau$) can be approximated by a straight line equation, the drying curve for this period can be described as follows:

$$\lg(\omega_2 - \omega_r) = -A \cdot \tau_{\mathrm{II}} + R \tag{11}$$

The above equation can be solved under the assumption that for τ_{II}=0, ω_2=ω_r and that the drying rate is equal to the drying rate in the first period [7]. As a result, the following relationship is obtained:

$$\lg\frac{\omega_2-\omega_r}{\omega_{cr}-\omega_r}=\lg E=-2.61\frac{\Delta T_m\cdot\alpha\cdot\Phi\cdot\tau_{II}}{(\omega_{cr}-\omega_r)r\cdot\rho_s\cdot d_s} \tag{12}$$

after converting equation (12), the kinetic equation for the second falling-rate period has the following form :

$$\ln E=-1.5NuFoKo^{-1}\left(\frac{\lambda_g}{\lambda_s}\right)\Phi \tag{13}$$

The above equation may be utilized on condition that the correlation for predicting the gas-solid heat transfer coefficient for the first constant rate period is known [3].

In order to attain the kinetic equation for both drying periods it is necessary to solve equations (8) and (12) for τ_I and τ_{II} and then add τ_I and τ_{II}. The obtained equation can he rearranged to the following form:

$$\frac{\omega_1-\omega_{cr}}{\omega_{cr}-\omega_r}-\ln E=1.5NuFoKo^{-1}\left(\frac{\lambda_g}{\lambda_s}\right)\Phi \tag{14}$$

The relationship (14) gives the kinetic equation for both drying periods.

EXPERIMENTAL PART

A scheme of experimental equipment is shown in Fig. 1. Polytetrafluoro-ethylene, ammonium sulphate, sand and silica gel were studied. Particle sizes ranging from $3.39\cdot10^{-4}$ to $12.4\cdot10^{-4}$m were used.

Experiments were carried out under the following conditions:

-inlet temperature of air 333K and 363K,
-static bed height 0.150 and 0.240m,
-air velocity from 0.2 to 1.8m/s.

For all the series of runs, the flow rate of air, the static bed height, the particle diameter and the inlet temperature of air were changed, whereas the initial moisture content of solid materials was constant.

EXPERIMENTAL RESULTS

208 experiments were carried out for the first constant-drying rate period and 97 runs were made, in which the drying kinetics of solid materials was studied for both periods of drying.

On the basis of the experimental results for the first period [3], the following correlation equation for the mean gas-solid heat transfer coefficient was worked out (Table 1 No. 15). It was found that there was a considerable effect of the shape factor Φ

of the solid particle on the value of α. This influence is reasonable, because the shape factor which depends on the shape and state of the surface [5], describes the real contact surfaces between the phases and hydrodynamic conditions.

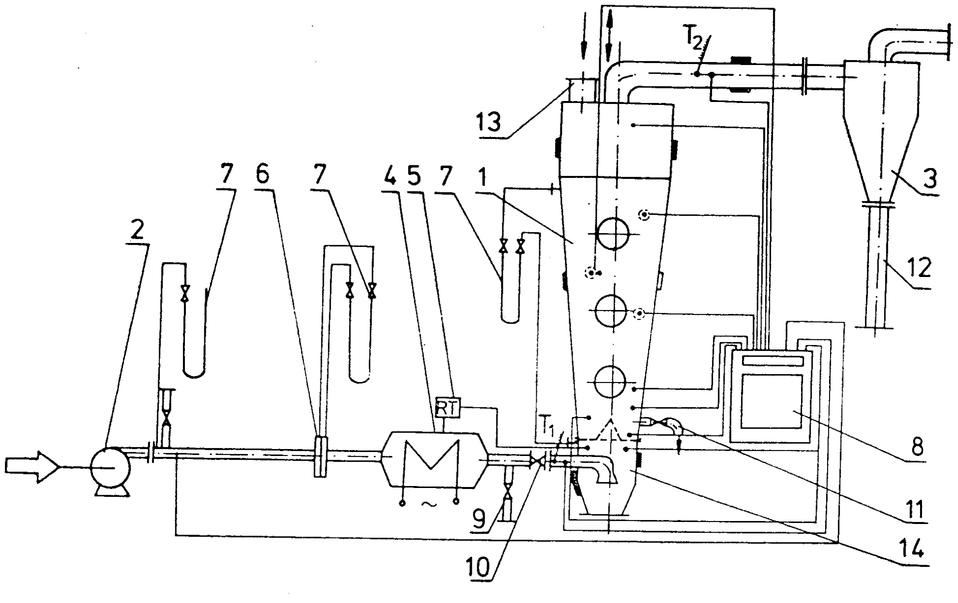

Fig. 1. Scheme of experimental equipment: 1-column, 2-blower, 3-cyclone, 4-electric heater, 5-thermoregulator, 6-orifice meter, 7-manometers two-fluid U-tubes, 8-temperature recorder, 9-pipe, 10-control valve, it-sample collector, 12-dust collector, 13-feeding pipe, T_1, T_2 - thermometers for the measurement of wet bulb temperature, 14-plenum chamber

A critical analysis of the experimental results [4] confirms the possibility of generalizing the rate curves, obtained under different conditions of runs.

The kinetic Equation (13), proposed for the second period, proves good agreement with the experiments (Fig. 2). The relative error of 85% of the experimental results is not higher than +10%.

Equation (13) holds for $0.88 < \ln E < 2.07$, $0.07 < (\lambda_g/\lambda_s) < 0.194$, $54.25 < Fo < 13.335$, $0.855 < Ko < 35.6$ and for the dimensionless groups ranges, for which the equation describing the Nusselt number is valid (Table 1, No. 15).

The general kinetic Equation (14) for both the constant rate and the falling rate periods holds for $0.88 < \ln E < 2.07$, $0.07 < (\lambda_g/\lambda_s) < 0.194$, $160 < Fo < 48.600$, $0.855 < Ko < 35.6$ This equation gives errors not higher than +15%.

If the process occurs only in the first period, Equation (14) becomes simplified ($\ln E$ cancels out).

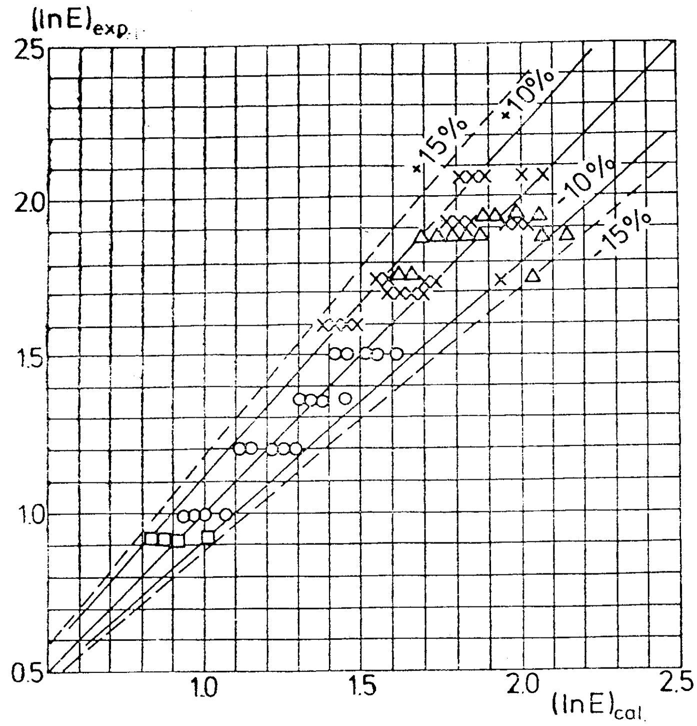

Fig. 2. Comparison of experimental and theoretical values of (ln*E*), O-silica gel, □–sand Δ-ammonium sulfate, X-polytetrafluoroethylene,

CONCLUSIONS

On the basis of the experimental results and literature studies the following conclusions were made.

1. Using the methods of generalizing the drying rate curves, the straight line approximation for describing the course of the first period of drying and the correlation equation for the mean gas - solid heat transfer coefficient in the constant drying rate period, there is a possibility of deriving the kinetic equation, which can be used for predicting the course of drying in both periods.
2. The kinetic equations for the second period (13) and for the periods of drying (14), including the shape factor of the solid particle (this parameter has not been taken into consideration so far), describe the actual drying conditions better than the correlation hitherto published. The proposed kinetic equations are of great utility for engineering calculations, because very few input data referring to the constant drying rate period are needed to solve them.

Symbols

a - specific surface, $m^2\ m^{-3}$
A - coefficient in Eq. (11)
C - heat capacity, $J\ kg^{-1}\ K^{-1}$
d_s - particle diameter, m
D_k - diameter in column, m
g - acceleration due to gravity, $m\ s^{-2}$
H_o - static bed height, m
m - mass, kg
N - drying rate in the first period, $kg\ kg^{-1}\ s^{-1}$
Q - heat – transfer rate, W
r - heat of vaporization, $J\ kg^{-1}$
R - coefficient in Eq. (11)
T - temperature, K
u_g - linear superficial gas velocity in empty column, $m\ s^{-1}$
V - solid volume in the dryer, m^3
ω - moisture constant (dry basis) of solid, $kg\ kg^{-1}$
α - heat transfer coefficient, $W\ m^{-2}\ K^{-1}$
ε - porosity
η - dynamic viscosity, $N\ s\ m^{-2}$
χ - relative drying coefficient Eq. (10), $kg\ kg^{-1}$
λ - thermal conductivity, $W\ m^{-1}\ K^{-1}$
ρ - density, $kg\ m^{-3}$
τ - time
Φ - shape factor, ($\Phi > 1$)
Δ - difference operator

Indexes

g - gas
m - mean
o - stationary bed
r - equilibrium
s - solid
u - bulk
cr - critical
1 - inlet, initial
2 - outlet, final
I - first drying period
II - second drying period

DIMENSIONLESS GROUPS

Archimedes	$Ar = \dfrac{d_s^3\left(\rho_s - \rho_g\right)}{\eta_g^2}\rho_g\rho$
Fourier	$Fo = \dfrac{\lambda_s \tau}{C_s \rho_s \left(\dfrac{d_s}{2}\right)^2}$
Kosovich	$Ko = \dfrac{r \cdot \left(\omega_{cr} - \omega_r\right)}{C_s \Delta T}$
Nusselt	$Nu = \dfrac{\alpha d_s}{\lambda_g}$
Prandtl	$Pr = \dfrac{C_g \eta_g}{\lambda_g}$
Reynolds	$Re = \dfrac{u_g d_s \rho_g}{\eta_g}$
dimensionless moisture concept	$E = \dfrac{\omega_2 - \omega_r}{\omega_{cr} - \omega_r}$
geometrical simplex	$\dfrac{H_0}{d_s}$

REFERENCES

1. Strumillo, Cz.: “Podstawy teorii i tecnhniki suszenia” (“Drying Principles and Practise”) – (in Polish) WNT, Warshaw, 1981.
2. Romankov, P. G., Rashkovskaya, N.B. and Frolov, V.F.: “Procesy wymiany masy w tecnologii chemicznej” (“Mass Transfer Processes in Chemical Tecnology”) – (In Polish) WNT, Warshaw, 1980.
3. Ciesielczyk, V. and Mrowiec, M.: Inz. Chem. i Proc., 1982, 3, (3-4), 523-538.
4. Ciesielczyk, V. and Mrowiec, M.: Inz. Chem. i Proc., 1982, 3, (2), 251-270.
5. Ciesielczyk, V. and Mrowiec, M.: Polish Patent 122611.
6. Perry, R.H. and Chilton, C.H.: “Chemical Engineers Handbook” McGraw-Hill, New York, 1973.
7. Romankov, P.G. and Rashkowskaya, N.B.: “Sushka vo Kipyashchem Sloe” (“Fluidized Bed Drying”) – (in Russian)I(ipj;asl.ielien Sloe" ("Fluidized Bed Drying"') - (in Russian) Khimiya, Moscow, 1964.
8. Kettenring, K.N., Manderfield, E.L. and Smith, I.M.: Chem. Eng. Progr., 1950, 40 (3), 139.
9. Meertjes, P.M. and McKibbins, S.W.: Chem. Eng. Sci., 1956, 5, 161.
10. Romankov, P.G. and Rashkovskaya, N.B.: “Sushka vo Vneshennom Sostoyanii” (Drying in the Suspended State) – (in Russian) Khimiya, Leningrtad, 1968.
11. Lykov, M.V.: “Sushka v Khimicheskoi Pramyshlennosti” (“Drying in the Chemical Industry”) – (in Russian), Khimiya, Moscow, 1970.
12. Kunii, D. and Levenspiel, O.: “Fluidization Engineering”. John Wiley and Sons. New York, 1969.
13. Wamsley, V.V. and Johanson, L.N.: Chem. Eng. Progr., 1954, 50 (7), 347.
14. Ju Chin Chu, Kalil, I. and Wetteroth, W.A.: Chem. Eng. Progr., 1953, 49 (3), 141.
15. Frantz, I.F.: Chem. Eng. Progr., 1961, 57 (7), 35.
16. Gelperin, N.I., Ainstein, V.G. and Kvasha, V.B.: “Osnovy Tehniki Psevdoozhizheniya” (Basic Techniques of Fluidization”) – (in Russian), Khimiya, Moscow, 1969.
17. Kmieć, A.: Inz. Chem., 1976, 6 (3), 497.

EKSPERIMENTALNO ISTRAŽIVANJE KINETIKE SUŠENJA ČVRSTIH ČESTICA U FLUIDIZOVANOM SLOJU

**Wlodzimierz Ciesielczyk, Mladen Stojiljković, Gradimir Ilić,
Nenad Radojković, Mića Vukić**

U radu je data jednačina kinetike sušenja za oba karakteristična perioda sušenja, na osnovu eksperimentalnih rezultata sušenja silikagela, politetra fluornog etilena, peska i amonijum sulfata u fluidizovanom sloju. Uvedena je korelaciona jednačina za odredjivanje koeficijenta prelaza toplote gas - čvrste čestice u konstantnom periodu sušenja. Ukazuje se na pogodnost uvodjenja faktora oblika čestica u jednačinu kinetike.