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DRYING OF SUSPENSIONS AND SOLUTIONS IN FLUIDIZED BED OF INERT PARTICLES – MATERIAL HOLD-UP AND ENERGY EFFICIENCY STUDY

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Abstract: The fluid bed dryer with inert particles was used as slurry dryer, producing a fine powder. Experiments were performed in a cylindrical column 215 mm in diameter and 1200 mm in height with glass spheres as inert particles (d_p=1.94 mm and 1.20 mm). Suspension of calcium hydroxide was used as the feed material in drying experiments. The physical phenomena occurring in this dryer was analyzed. In this paper, energy efficiency of the process and the dried material residual content in the bed were experimentally determined. A number of experiments were carried out in the pilot plant fluidized bed dryer of the nominal evaporation capacity of 20 kg_{H2O}/h and the influence of the choice of the process parameters on energy efficiency of the system was investigated, taking into account the specific conditions that need to be satisfied.
Keywords: drying, fluidized bed, suspensions, powder, energy efficiency, hold-up

1. INTRODUCTION

Many processes in chemical, pharmaceutical and food processing industries involve drying of solutions, suspensions and pastes in order to obtain the final product in the form of powder. Various drying techniques can be used for this purpose, depending on the initial moisture content and physical and rheological properties of the material. In general, trends in drying technology are associated with achieving higher energy efficiency, enhanced drying rates, development of more compact dryers, better control for enhanced quality and optimal capacity, developments of multi-processing units (for example filter-dryer) [1].

Drying of slurries on inert particles is a relatively novel technology to produce powdery materials. It was originally developed for drying of pigments, chemicals and some biomaterials to eliminate constrains of spray, drum and paddle dryers. Classical fluid bed, spouted bed, spout-fluid bed, jet spouted bed and vibrated fluid bed are the most popular dryers used for drying on inert particles [2-10]. The principle behind this technology is based on drying of a thin layer of the slurry that coats the surface of inert particles. Depending on the dryer type, these particles can be vibrated, fluidized or spouted either by hot air only, or in combination with a mechanical device installed within the dryer, such as an agitator or conveyor screw. A high drying efficiency results from the large contact area and from the large temperature difference between the inlet and outlet air. The generalized diagram of a fluidized bed drying system is presented in Figure 1. The feed material is directly supplied into the column where inert particles are fluidized by hot air. The product is separated from the exhaust air by a cyclone and a bag filter. The drying mechanism depends on the feed slurry density and consistency, as illustrated schematically in Figure 2. If the feed is relatively diluted (a solution or a suspension) the drying mechanism consists of three steps, which occur simultaneously in different regions of the bed. The charged material forms a film, which adheres to the surface of inert particles. Because of the very large surface area of the particles and intensive fluidization, moisture is removed in the time frame of few seconds.

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Solids remaining on the surface of inert particles are peeled off by friction and collisions. Finally, the powdery product is elutriated from the inert bed with the exhaust air (Figure 2a). If the feed is a dense slurry (paste) then wet paste aggregates fluidize together with the inert particles. During the drying process the size of aggregates decreases due to elutriation of dried particles from the bed surface (Figure 2b). In this case, a more homogenous and stable bed can be obtained by incorporation of a low-speed mechanical mixer. Note that a typical dry particle is about two orders of magnitude smaller than the inert particles in the bed. Due to the intensive mixing of inert particles during fluidization the bed temperature is approximately uniform.

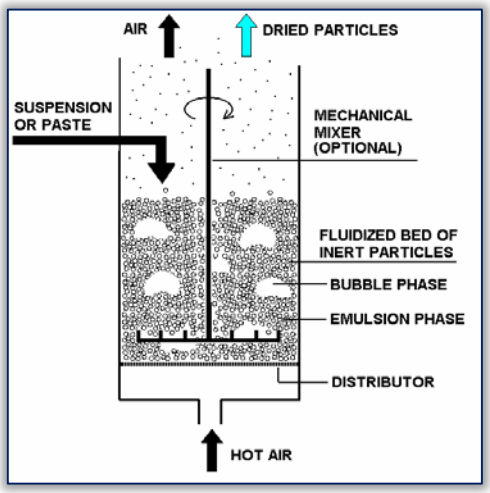

Figure 1. Drying of suspensions in a fluidized bed of inert particles [8, 11]

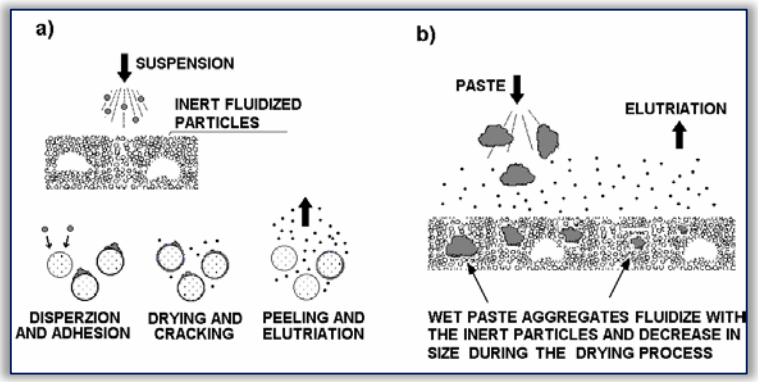

Figure 2. The drying mechanism: a) feed – suspension, b) feed – paste [8, 11]

Different investigations, with wet materials of varied nature, have shown that considerable product accumulation occurs on the surface of the inert particles. Thereupon, the dryer productivity is limited by cleaning of the surface of inert particles from the dried product [12-14]. Since the steady state drying can be achieved only if the drying time is shorter than coating time [15], the knowledge of the product hold-up in the bed is of great importance.

2. EXPERIMENTAL

The experimental set up is schematically shown in Figure 3. The drying chamber is a cylindrical column D_c = 215 mm i.d. and 300 mm high, connected by a conical section with the 320 mm i.d. and 300 mm high upper cylinder. The overall column height is 1200 mm, where the effective column height (above the distributor) is 900 mm. The inert particles were glass spheres with the mean diameter d_p = 1.94 mm (density 2460 kg/m^3) and d_p = 1.20 mm (density 2640 kg/m^3). The inert bed mass of larger glass particles was 5.6 kg, static bed height was 101 mm and the total inert particle area was 7.2 m^2, whereas for the smaller particles these values were 5.9 kg, 99 mm and 11.2 m^2, respectively. Minimum fluidization velocity was determined at ambient air temperature using standard procedure (U_{mF} = 1.00 m/s for d_p = 1.94 mm, and U_{mF} = 0.71 m/s for d_p = 1.20 mm). Superficial air velocity (at ambient temperature) was 1.76 m/s, inlet air temperature (T_{gi}) was nearly constant at 200°C, whereas the outlet air temperature (T_{ge}) was in the range of 60 to 120°C. The water content in the feed materials varied between 0.60 and 0.95 kg_{H2O}/kg_{sus}. The feed material is directly pumped into the bed axis using a peristaltic pump for suspensions and the feed outlet is located 100 mm above the gas distributor.

The product is separated from the air stream in a cyclone and a bag filter. Before leaving the system, the exhaust air is passed through a packed bed scrubber. A temperature controller TIC1 maintains the inlet air temperature at the desired level. A temperature controller TIC2, which is located 0.7 m above the distributor plate and connected with a feeding device, keeps the outlet air temperature constant (T_{ge}). A temperature controller TIC3, which is also placed 0.7 m above the distributor plate, is set at a temperature 20°C above the outlet air temperature. Its role is to prevent overheating of the bed, in the case of feeding device failure, by introducing pure water into the system. During experiments, the inlet air temperature and outlet air temperature were continuously recorded using a PC and a data acquisition system. Two set of experiments were performed with Calcium(II)-hydroxide suspension $Ca(OH)_2$ with glass spheres of 1.94 mm and 1.20 mm.

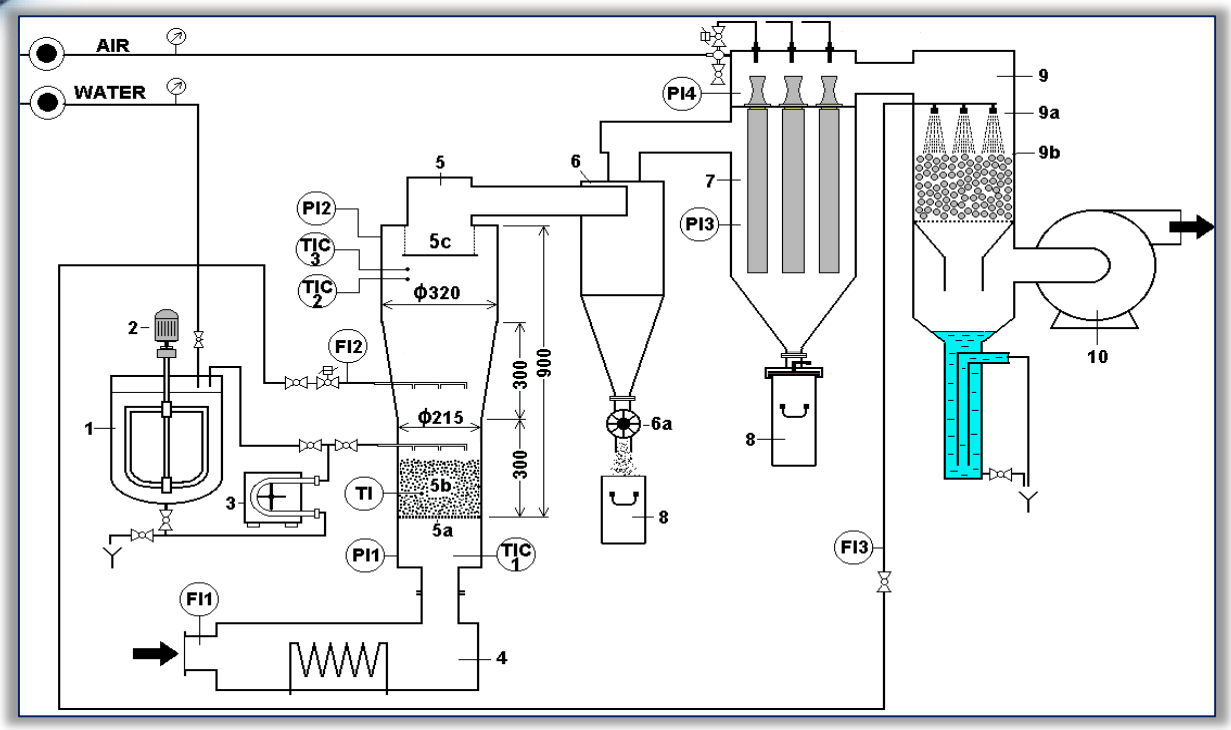

Figure 3. Schematic diagram of the drying system
(1 - Tank, 2 - Agitator, 3 - Pump, 4 - Air heater, 5 - Fluidization column, 5a - Distributor, 5b - Inert particles, 5c - Deflector, 6 - Cyclone, 6a - Rotary valve, 7 - Bag filter, 8 - Product containers, 9 - Scrubber, 9a - Nozzle, 9b - Packing, 10 - Blower, FI - Flowrate indicator, PI - Pressure indicator, TI - Movable temperature probe, TIC - Temperature indication and control)

3. RESULTS AND DISCUSSION

—Drying experiments

The drying tests were performed continuously. For all runs, the desired air flowrate and air inlet temperature (TIC1) were selected. When the temperature above the bed (outlet air temperature) reached the set value (TIC2), the feeding process begun. In the further process the outlet air temperature was constant since TIC2 controls the feeding device. The stationary state was reached after several minutes since inlet air temperature had reached the set value TIC1. The system was very stable, i.e. during the operation the outlet air temperature variations (ΔT_{ge}) were less than 5°C. Each suspension was characterized by the water content and density, while each dried sample was characterized by the residual water content and bulk density.

—Maximum feed rate

It was observed in our drying experiments that maximum feed rate securing stable hydrodynamics increases with the inlet air temperature. It also increases with the static bed height because of larger interfacial area is available for heat and mass transfer. The maximum feed rate increases with superficial air velocity as a result of more intense fluidization and enhanced evaporation rate due to higher heat transfer coefficients. These parameters can be set in such way to approach the optimum feed rate defined by energy efficiency and product moisture content. In order to obtain maximum process efficiency for a fixed inlet air temperature (T_{gi}), the outlet air temperature (T_{ge}) should be as low as possible with respect to the product quality and quality of fluidization. Usually, the residual moisture content of the product powder is the main criterion. Generally the powder moisture content decreases with an increase in outlet air temperature, as shown in Figure 4. However, the shape of this relationship depends on dried material characteristics. It can be seen that the residual powder moisture content is essentially independent of outlet air temperature above T_{ge}=100°C.

—Material hold-up

The hold-up of the dried material on inert particles was measured. When temperatures of inlet and outlet air were nearly constant, suspension was fed continuously to the drying chamber. The experiments were run for additional 10-15 minutes after the steady state was reached with suspension feed. Then the air stream and suspension feed were stopped for a short time, which was

enough to extract a sample of the bed. The sample was weighed, and the product film held on particles was washed off and then the mass of particles and the dry film were obtained in order to determine the material hold-up. The suspension used for this purpose was calcium hydroxide. For inert particles d_p = 1.94 mm, the hold-up varied between 7.2 and 24.2% and for inert particles d_p = 1.20 mm between 3.8 and 33.8% with respect to the inert bed mass. Based on these values, it can be observed that the higher hold-up is for the smaller particles. Mass of the product held by a unit of inert particles (m) varies from 0.02 to 0.19 kg/m^2. Assuming that the bulk density of a material surrounding inert particles is an arythmetic from the mean slurry and dry powder densities, a hypothetical thickness of the material film covering an inert particle (f) can be estimated. The calculations shows that the film thickness varies from 8.9 to 80.3 µm. Figure 5 clearly shows how the film thickness increases with the subsequent experiment, independent of the suspension concentration and temperature. For particles d_p=1.94 mm film thickness is about 80 µm, while for particles d_p=1.20 mm, the thickness is about 70 µm. This is a clear indication that cumulative formation of calcium hydroxide film on the particle surface occurs.

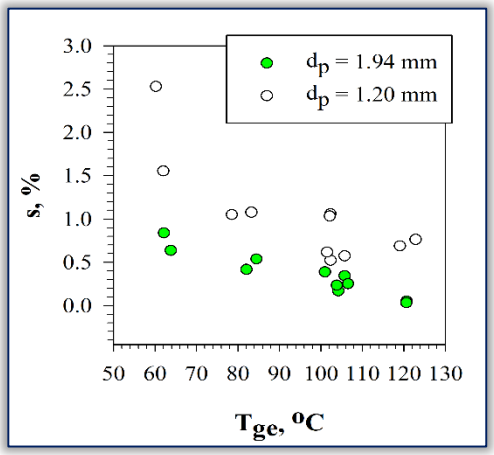

Figure 4. Product moisture content as a function of drying temperature

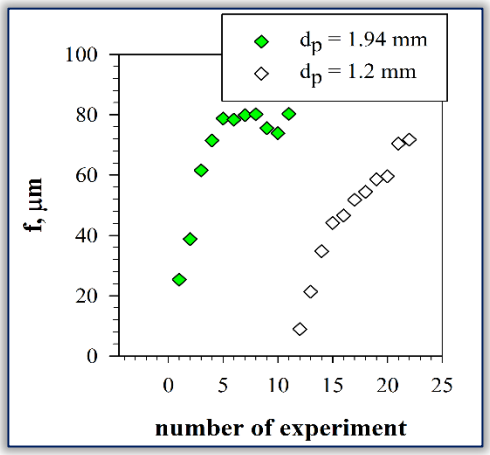

Figure 5. The thickness of the formed film on the particle surface through experiments

Mechanical grinding of the dried product from the inert particle, which determines the average thickness of this film and, consequently, the product hold-up, which is usually not constant because it depends on the process parameters, is not simple to be described quantitavely. It essentially depends on the adhesive properties of the product to the inert particles. As the viscosity of dried material is higher, the hold-up will be more pronounced [14]. Also, the material hold-ups are different for different types for inert particles, and Pan et. al. [16] observed that the soybean milk hold-up in the bed of Teflon pellets is lower than that in the bed of glass ballotini up to 15%. Stability of the drying process in fluidized bed depends on the shaking of the dried material and carrying off the powder. If stationary state conditions are not achieved the drying process would convert to that of coating. The coating process can be successfully achieved in such systems, but in the present investigation it was an unwanted effect.

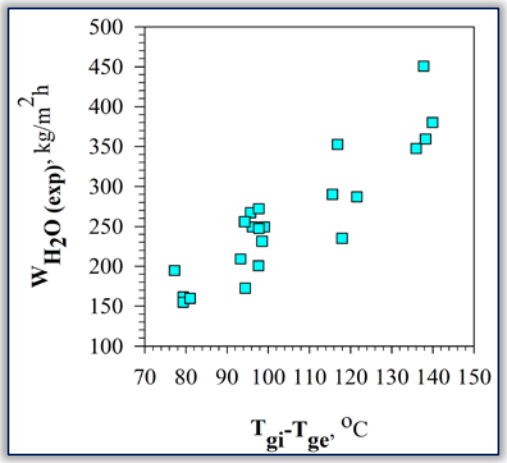

Figure 6. Specific water evaporation rate for $Ca(OH)_2$ suspension as a function of the temperature difference between the inlet and outlet air temperatures

— Specific water evaporation rate

Figure 6 presents the specific water evaporation rate (kg_{H2O}/m^2h) as a function of the temperature difference (T_{gi}- T_{ge}), where T_{gi} and T_{ge} are the inlet and outlet air temperature, respectively. It can be seen that evaporation for a fixed gas velocity is directly proportional to the temperature difference. The highest evaporation rate in our runs was 451 $kg_{H2O}m^{-2}h^{-1}$ at the superficial air velocity (calculated at 20°C) of U_0 = 1.76 ms^{-1} and at the inlet air temperature of T_{gi}=200°C and the outlet air temperature of T_{ge}=62°C.

— Energy efficiency

Energy efficiency of a dryer, as well as the operating regime in which the drying process takes place, can be described using various parameters, such as the volumetric evaporation rate, heat losses to the environment, specific heat consumption and thermal (energy) efficiency. Of all the mentioned parameters, the most commonly encountered in the technical literature is the thermal efficiency [1,2,17]. This parameter (η'_T, η''_T or η_T) mainly relates the amount of heat required for evaporation of moisture calculated in relation either to the temperature of the surface of inert particles (T_p) or to the ambient temperature (T_0) or to the wet bulb temperature (T_{wb}), respectively, with the total energy brought to the dryer. Thus, it is defined by one of the following equations:

$$\eta'_T = \frac{(T_{gi} - T_{ge})}{(T_{gi} - T_p)}, \quad or \quad \eta''_T = \frac{(T_{gi} - T_{ge})}{(T_{gi} - T_{wb})}, \quad or \quad \eta_T = \frac{(T_{gi} - T_{ge})}{(T_{gi} - T_0)} \tag{1}$$

In Figure 7 the thermal efficiency, η_T, calculated in relation to the ambient temperature according to the Eq. (1) is shown for different inlet air temperatures. As can be seen, the thermal efficiencies are in the interval η_T = 0.44÷0.78 in our system for all the performed experiments with $Ca(OH)_2$ suspension, compared to $\eta_T \approx 0.3$ reported for soybean milk drying in a vibro-fluidized bed at similar operating conditions ($T_{gi} \approx$ 150-160 °C) [17]. Drying efficiency increases with the increase in the temperature difference. This would mean that for a fixed inlet air temperature (T_{gi}), the drying temperature (T_{ge}) should be as low as possible in order to maximise the temperature difference T_{gi}-T_{ge}. The main factors influencing the choice of the T_{ge} value are the product quality and quality of fluidization. Usually, the residual moisture content of the product powder is the main criterion.

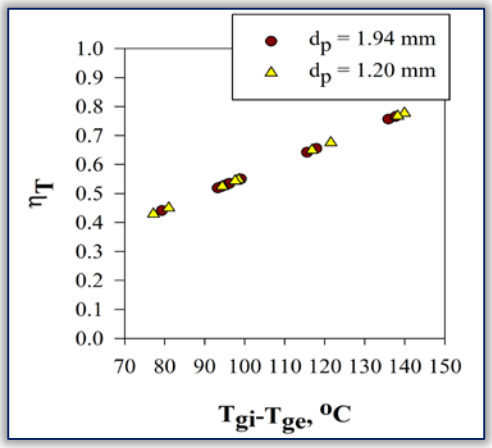

Figure 7. Thermal efficiency as a function of the temperature difference between the inlet and outlet air temperatures

— Heat and mass balances

From the overall mass and heat balance follows a simple relationship between the inlet air temperature (T_{gi}) and the specific water evaporation rate (W_{H2O}) [8, 11]:

$$W_{H_2O} = \frac{G_{H_2O}}{A_c} = \frac{1}{A_c} \cdot \frac{G_v c_v \left(T_{gi} - T_{ge}\right) - Q_g}{\left[(1-x)/x\right] c_{dm} \left(T_{ge} - T_0\right) + c_{H_2O}\left(T_{ge} - T_0\right) + r_{H_2O}} \tag{2}$$

For a fixed geometry of the fluidized bed (A_c), the air flowrate, i.e., the superficial air velocity follows from the fluid bed mechanics and it should be usually 2–3-fold higher than the minimum fluidization velocity (U_{mf}). A comparison between experimental and calculated values of W_{H2O}, by using $c_{dm} \approx 1.18$ kJ kg^{-1}°C^{-1}, is shown in Figure 8. The mean absolute deviation between the experimental and calculated values is 9.2%, while 85% of the data falls within ±10%. Differences between the experimental and calculated values are probably due to the fact that heat losses were neglected in the calculations.

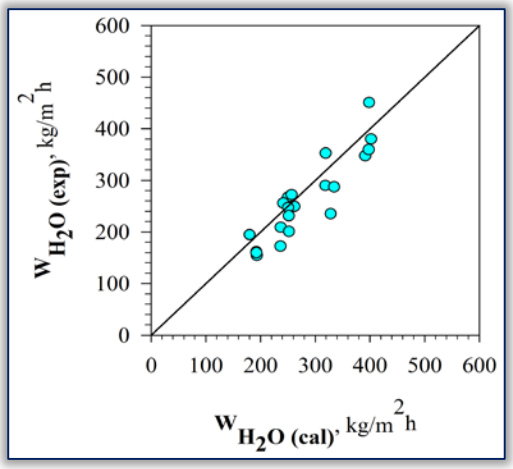

Figure 8. Comparison of the experimental and calculated values of the specific water evaporation rate

4. CONCLUSION

Drying of solutions, suspensions and pastes in a fluidized bed of inert particles is characterized by high evaporative capacity per unit volume of the dryer, low energy consumption, and low specific air consumption. The high drying efficiency results from the large contact area and from the large temperature difference between the inlet and outlet air. Intensive mixing of particles leads to nearly isothermal conditions throughout the bed. Powdery product moisture content decreases with an increase in outlet air temperature and the shape of

this relationship depends on dried material characteristics. Inlet air temperature, superficial air velocity and static bed height can be set in such way to approach the optimum feed rate defined by energy efficiency and product moisture content.

NOMENCLATURE

Latin symbols

A_c – Cross-sectional area of the column at distributor plate, m^2

A_p – Total area of the inert particles in the fluidized bed, m^2

c_{dm} – Specific heat of dry matter, kJ kg^{-1} K^{-1}

c_{H2O} - Specific heat of water, kJ kg^{-1} K^{-1}

c_v – Specific heat of air, kJ kg^{-1} K^{-1}

d_p – Inert particle diameter, m

D_c – Column diameter (at distributor plate), m

f – Hypothetical thickness of the material film covering an inert particle, μm

G_{dm} – Mass flowrate of dry matter, kg s^{-1}

G_{H2O} – Water mass flowrate, kg s^{-1}

G_{sus} – Suspension mass flowrate, kg s^{-1}

G_v – Air mass flowrate, kg s^{-1}

M – Mass of the bed of inert particles, kg

m – Mass of the product held by a unit of inert particles, kg m^{-2}

q – Specific heat consumption, based on T_{gi}-T_{ge}, kJ kg_{H2O}^{-1}

q' – Specific heat consumption, based on T_{gi}-T_0, kJ kg_{H2O}^{-1}

Q_g – Heat losses, kJ s^{-1}

r_{H2O} – Latent heat of water evaporation, kJ kg_{H2O}^{-1}

s – Product moisture content, %

kg_{H2O}^{-1}

T_{gi} – Inlet air temperature, °C

T_{ge} – Outlet air temperature, °C

T_0 – Ambient temperature, °C

T_{wb} – Wet bulb temperature, °C

U_0 – Superficial fluid velocity at distributor plate (at T_0), ms^{-1}

U_{mF} – Minimum fluidization velocity at distributor plate (at T_0), ms^{-1}

V_0 – Air flowrate (at T_0), m^3 s^{-1}

W_{H2O} – Specific water evaporation rate(=G_{H2O}/A_c), kg $m^{-2}s^{-1}$

x – Water content in the suspension (G_{H2O}/G_{sus}), kg kg^{-1}

Greek symbols

η_T – Thermal efficiency, in relation to the ambient temperature (T_0)

η'_T – Thermal efficiency, in relation to the temperature of the surface of inert particles (T_p)

η''_T – Thermal efficiency, in relation to the wet bulb temperature (T_{wb})

Note: This paper is based on the paper presented at IIZS 2019 – The 9th International Conference on Industrial Engineering and Environmental Protection, organized by Technical Faculty "Mihajlo Pupin" Zrenjanin, University of Novi Sad, in Zrenjanin, SERBIA, in 03–04 October, 2019.

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References

[1] Mujumdar AS. Handbook of Industrial Drying. 4th ed., New York, NY: Marcel Dekker; 2014.
[2] Kudra T., Mujumdar AS. Advanced Drying Technologies. 2nd ed., New York, NY: Marcel Dekker; 2009.
[3] Kudra T, Mujumdar AS. Special Drying Technologies and Novel Dryers. In Mujumdar AS, ed. Handbook of Industrial Drying. 4th ed., New York, NY: Marcel Dekker; 2009:1087-1149.
[4] Reger EO, Romankov PG, Rashkovskaya NB. Drying of Paste-like Materials in Spouted Beds with Inert Bodies. Zhurn.Prikl.Khim. 1967; 40:2276. (in Russian)
[5] Romankov PG. Drying. In: Davidson JF, Harrison D, eds. Fluidization. London: Academic Press; 1971:569-598.
[6] Pham QT. Behavior of a Conical Spouted-Bed Dryer for Animal Blood. Can.J.Chem.Eng. 1983; 61:426-434.
[7] Hadžismajlović DžE, Povrenović DS, Grbavčić ŽB, Vuković DV, Littman HA. Spout-Fluid Bed Drier for Dilute Solutions Containing Solids. In: Grace JR, Shemilt LW, Bergougnou MA, eds. Fluidization VI. New York, NY: Engineering Foundation; 1989:277-283
[8] Grbavcic ZB, Arsenijevic ZL, Garic-Grulovic RV. Drying of slurries in fluidized bed of inert particles. Drying Technol. 2004; 22:1793-1812.
[9] Arsenijevic Z. Drying suspension in the industry, 1st ed. Serbia, Andrejevic Foundation; 2008. (in Serbian)
[10] Reyes A, Diaz G, Marquardt F-H. Analysis of Mechanically Agitated Fluid-Particle Contact Dryers. Drying Technol. 2001; 19:2235-2259.
[11] Grbavcic ZB, Arsenijevic ZL, Garic-Grulovic RV. Drying of suspension and pastes in fluidized bed of inert particles. J.Serb.Chem.Soc. 2000; 65:963–974.
[12] Vieira, M.G.A., Donida, M.W. and Rocha, S.C.S., Adhesion of an aqueous polymeric suspension to inert particles in a spouted bed, Drying Technol., 22 (2004) 1069-1085.
[13] Leontieva, A.I., Bryankin, K.V., Konovalov. V.I. and Utrobin, N.P., Heat and mass transfer during drying of a liquid film from the surface of a single inert particle, Drying Technol. 20 (2002) 729-747.
[14] Spitzner Neto, P.I., Cunha, F.O. and Freire, J.T., Effect of the presence of paste in a conical spouted bed dryer with continuous feeding, Drying Technol. 20 (2002) 789-811.
[15] Kutsakova, V.E., Drying of liquid and pasty products in a modified spouted bed of inert particles, Drying technol., 22 (2004) 2343-2350.
[16] Pan, Y.K., Li, J.G., Zhao, L.J., Ye, W.H., Mujumdar, A.S. and Kudra, T., Performance characteristics of the vibrated fluid bed of inert particles for drying of liquid feeds, Drying Technol., 2001 19(2001) 2003-2018.
[17] Pan YK, Li JG, Zhao LJ, Ye WH, Mujumdar AS, Kudra T. Performance characteristics of the vibrated fluid bed of inert particles for drying of liquid feeds. Drying Technol. 2001; 19:2003-2018.