Material hold-up on inert particles in fluidized bed dryer

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Abstract

In this paper the influence of process parameters on the material hold-up in a fluidized bed dryer with inert particles was investigated. The experiments were performed in a pilot-scale dryer with a cylindrical column 0.215 m in diameter and 1.2 m height, with glass spheres of diameters d_p = 1.20 mm and 1.94 mm as inert particles. The material used for drying was $NaHCO_3$ slurry of two different concentrations, 10 and 20 wt.%. Dynamics of the material hold-up was determined for four different drying temperatures, in the range from 60 to 120 °C by taking the samples of coated particles during the drying process and measuring the mass with and without the coated material film. The obtained results showed strong positive dependence of the material hold-up on the initial slurry concentration as well as on the drying temperature. The rate of the material film coating formation is quicker at higher drying temperatures.

Keywords: Drying; slurry; powder material; process parameters; concentration; temperature.

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1. INTRODUCTION

Drying of solutions, slurries, and pastes to obtain the final product in powder form is a widespread process in chemical, pharmaceutical and food processing industries. There are many different techniques that can be applied for this purpose. The choice of the technique mainly depends on the initial moisture content and physical and rheological properties of the material to be dried. Techniques with better energy performance are favored, in combination with high drying rates and better control of the process. Both pre-drying and post-drying stages have an important influence on the selection of the appropriate dryer type for a particular application. Each type of dryer has specific characteristics that make it suitable or unsuitable for certain applications [1].

Drying of slurries in fluidized beds of inert materials was originally developed for drying pigments, chemicals, and some biomaterials to eliminate disadvantages of spray, drum, and paddle dryers [2-5]. This technology is based in principle on drying a thin layer of the slurry covering the surface of the inert particles (Figure 1) [6]. The main advantages of this drying process compared to other drying methods are: efficient heat and mass transfers due to the constant motion of particles; uniform drying as the particles are well mixed in the bed; high surface area-to-volume ratio of the fluidized bed which allows for efficient removal of moisture from the particles; better preservation of the dried product quality due to gentle fluidization and controlled drying conditions in the fluidized bed.

Mechanism of fluidized bed drying consists of three steps that occur simultaneously in different areas of the bed. In the first step, the slurry material forms a film that adheres to the surface of the inert particles. In the second step, the moisture is removed from the film material within very short time periods. The dry material remains in the form of a coating on the inert particle surfaces. In the final step, the coating is peeled off by friction and collisions and the dry material leaves the bed with the air stream. This final step is regarded as the critical step in the process, since the rate of material removal controls the magnitude of the surface available for the new material and establishment of a dynamic equilibrium in the system.

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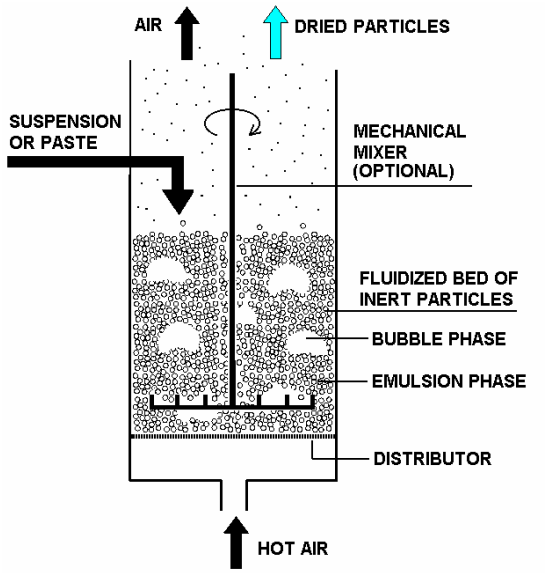

Figure 1. Drying of slurries in a fluidized bed of inert particles

Drying of fungicides and pesticides, other inorganic compounds and complexes was successfully tested in a semi-industrial plant for drying slurries and pastes in a fluidized bed of inert glass spheres [4-9]. Compared to other drying systems, this system can achieve several fold higher specific capacities per unit volume of the unit and thus lower investment costs. Other advantages of this process are continuity, elimination of the subsequent step of grinding of the powdered product, and significantly lower energy consumption per unit of evaporated moisture. The system is stable and very efficient. The efficiency of the system, expressed by the specific evaporation rate, specific heat consumption, and specific air consumption, is higher when the system operates at a larger temperature difference between the incoming air and the bed of inert particles. Due to the intensive mixing of the particles, the temperature of the bed is uniform throughout the volume thus avoiding the risk of local overheating. Stability of the process in terms of product quality (residual moisture) is decisively influenced by the stability of the flow of the input slurry or paste. In this system it is possible to treat all materials that do not stick together with inert particles [5,7].

Drying of slurries in a modified spouted bed with a draft tube is an attractive solution for drying of various organic and biological materials, which are generally sticky. For stable operation of the system, it is extremely important to achieve conditions where the slurry film on the surface of inert particles is completely dry after passing through the draft tube, as otherwise the inert particles in the annular zone may stick together and the bed may sinter. A drying model was developed based on a one-dimensional hydrodynamic model of a turbulent two-phase gas-mass particle flow in the acceleration zone, combined with mass and heat transfer balances along the draft tube. Such a model provides useful information for the design of dryers and for the simulation of drying processes [8,9].

A model was established previously to predict the particle circulation rate in a dryer with a spouted bed of inert particles and a central tube [10]. The proposed model was verified experimentally. Three quantities are known in the calculation algorithm (input parameters): gas velocity through the draft tube, the static pressure value in the draft tube, and the pressure gradient in the annular zone. The particle circulation velocity is calculated by using continuity and momentum balance equations for turbulent two-phase fluid-particle flow.

In previous studies, influences of the initial composition and nature of the slurry and thermal parameters of drying on continuity of the process were studied by observing accumulation of the dried material in a bed of inert particles over time and changes in fluid dynamic parameters [11,12]. Based on these investigations, a technical solution for a plant for drying slurries and pastes in a fluidized bed of inert material was created, *i.e.* an industrial prototype with an evaporation capacity of 650 kg_{H_2O} h^{-1} was realized, which has been in operation since March 2003.

Drying in a fluidized bed of inert particles is continually investigated due to its broad applications, possibilities for process optimization, improved quality, and achievement of energy efficiency. These studies contribute to further

understanding and development of this important industrial process [13-16]. Specific details and effectiveness of a spouted bed of inert particles drying system with draft tube depend on the specific application, type of inert particles used, process conditions, and other factors. Therefore, these systems are still being studied in detail to properly implement this drying process [17,18].

Hold-up in fluidized bed drying refers to the amount of material that is retained as a coating of inert particles within the bed during the drying process. It represents a fraction of the total dry powder that remains within the fluidized bed rather than being carried away by the drying air. The hold-up is influenced by various factors, including properties of the material being dried, such as particle size, density, and surface characteristics, as well as by operating parameters of the fluidized bed dryer.

Measuring and understanding hold-up dependence relations in fluidized bed drying is important for process optimization, as it helps determining the efficiency of the drying process and the extent of drying achieved. It also aids in designing and sizing the equipment, as well as evaluating the potential for material loss or carryover in the system.

Although there iwerextensive literature covering applications of fluidized bed of inert particles in drying of inorganic slurries and pastes and efficiencies of the process, there are only a few papers in which the influence of process parameters on the material hold-up on inert particles was investigated [11,12]. This information can be of great importance as it provides insights into potential optimal conditions under which the process can be operated.

In this paper, influences of the inert particle size and the bed temperature on the hold-up of $NaHCO_3$ in a fluidized bed dryer were investigated. The experiments were performed for two different particle sizes and four drying temperatures. The $NaHCO_3$ slurries of two different concentrations were used.

2. EXPERIMENTAL

Drying of $NaHCO_3$ slurries was performed in an experimental set-up schematically shown in Figure 2.

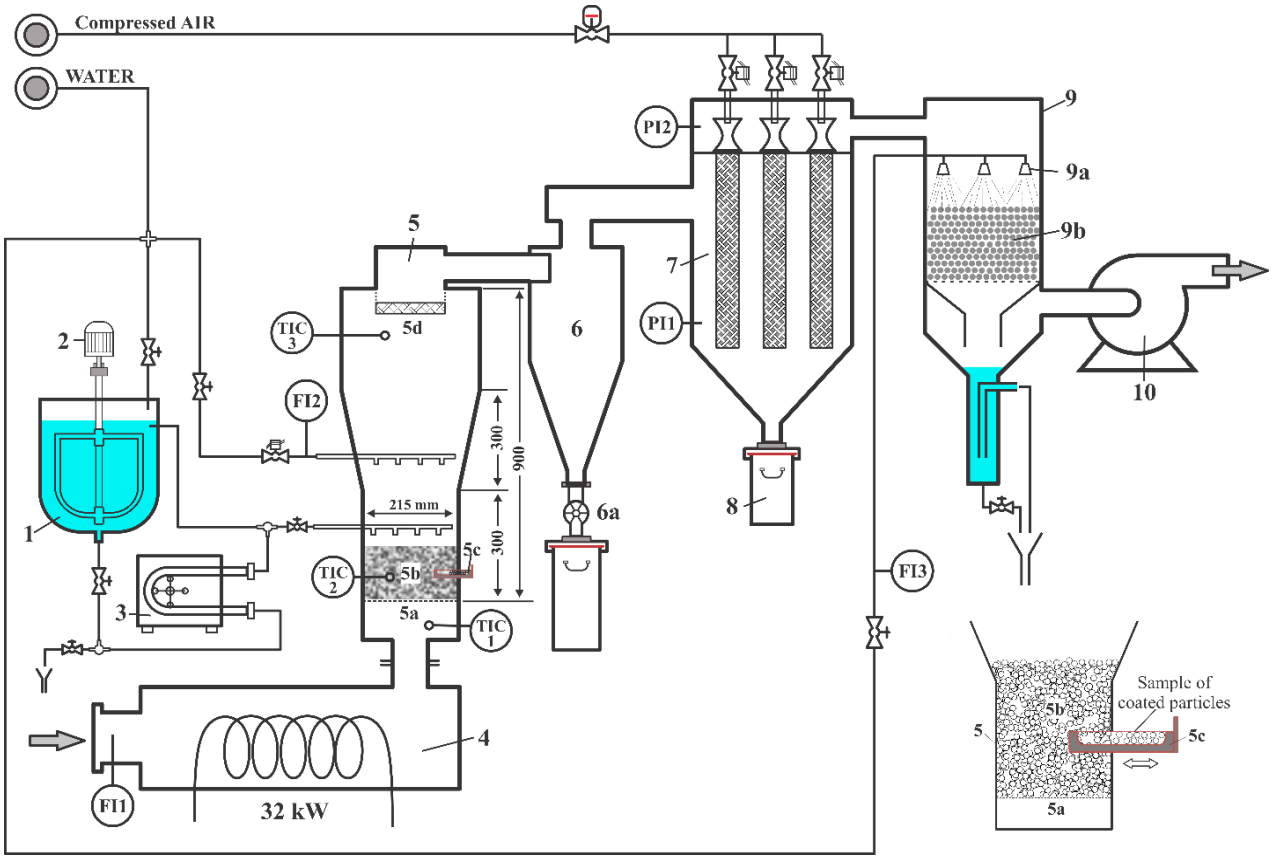

Figure 2. Fluidized bed dryer experimental set-up: 1-tank, 2-agitator, 3-pump, 4-air heater, 5-fluidization column, 5a-distributor, 5b-inert particles, 5c-scoop, 5d-deflector, 6-cyclone, 6a-rotary valve, 7-bag filter, 8-product containers, 9-scrubber, 9a-nozzle, 9b-packing, 10-blower

The main parts of the experimental set-up are fluidized bed of inert particles in which the drying process takes place, agitated slurry tank (1) with slurry pump (3), inlet air heater (4) and air blower (10). The fluidized bed column consisted of a cylindrical and a conical part (5). Dimensions of the cylindrical column are D_c = 215 mm i.d. and H = 300 mm, while the height of the conical section was 300 mm. An air blower is located at the end of the line in order to prevent material loss through fittings (the whole set-up operates under vacuum conditions). After the drying process, the powder is separated from the hot air stream by using a cyclone (6) and a bag filter (7). Before leaving the system, the exhaust air passes through a packed bed scrubber (9) in order to remove any residual particles. Besides these main elements, the set-up contains temperature probes, temperature indicators and controls, and flowrate and pressure indicators.

Temperature controller TIC1 maintains the inlet air temperature at the desired level. Temperature controller TIC2, which is located 0.7 m above the distributor plate and connected to a feeding device, keeps the outlet air temperature constant (T_{ge}). 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 the experiments, the inlet and outlet air temperatures were continuously recorded by using a data acquisition system.

The cylindrical drying section of the fluidized bed was equipped with a specially designed scoop (5c) in order to allow for the extraction of coated inert particles at different time points during the experiment. At these occasions, a sample of 20 to 30 g of particles was taken out of the fluidization column at time intervals of 10 minutes. It was assumed that the mass of the removed particles is negligible as compared to the total mass of the fluidized bed. The removed coated particles were precisely weighted, and then were thoroughly cleaned of the dry material and rinsed in a fine mesh to reduce the possibility of particle loss. The hold-up of the material on the particle surfaces was calculated based on the mass difference between the coated and washed particles. In the experimental investigations, 2 types of inert glass spherical particles were used (Table 1). The minimum fluidization velocity of the particles used was determined in our previous work [19]. The experiments were performed using $NaHCO_3$ slurry concentrations of 10 and 20 wt.%. The inlet air temperature (T_{gi}) was maintained at 200 °C in all experiments, whereas the outlet air temperature (T_{ge}), which is the same as the bed temperature in the fluidized bed dryer was in the range 80 to 140 °C. The slurry flow rate was regulated so as to keep the bed temperature constant.

Table 1. Characteristics of the two types of inert glass particles

Inert particles	**d_p / mm**	**ρ / kg m^{-3}**	**U_{mF} /m s^{-1}[19]**
A	1.94	2640	1.114
B	1.20	2460	0.785

The experimental conditions are shown in Table 2.

Table 2. Experimental conditions in drying of $NaHCO_3$ slurries

Exp. No	Slurry concentration, wt.%	T_{gi} / °C	T_{ge} / °C	ΔT / °C	t / min	G_{sus} / kg h^{-1}
Particles A; d_p=1.94 mm, M_{bed}=5.00 kg						
1	10	200	60	140	135	15.70
2	10	200	80	120	160	13.53
3	10	200	100	100	170	11.57
4	10	200	120	80	165	8.98
5	20	200	60	140	126	16.59
6	20	200	80	120	147	14.45
7	20	200	100	100	135	11.17
8	20	200	120	80	194	9.33
Particles B: d_p = 1.20 mm, M_{bed} = 5.50 kg						
9	10	200	60	140	130	16.18
10	10	200	100	100	168	10.72
11	10	200	120	80	208	8.72
12	20	200	60	140	145	16.51
14	20	200	100	100	154	11.71
15	20	200	120	80	209	8.61

The mass flow rate of the slurry, G_{sus}, depended on the driving force ΔT, *i.e.* the temperature difference between T_{gi} and T_{ge}. ΔT was in the range between 80 and 140 °C.

General parameters of $NaHCO_3$ slurry drying in the fluidized bed of inert particles were determined: product residual moisture content and specific water evaporation rate.

The product residual moisture content was determined by drying the sample of the product from each run to the constant mass, and then determining the mass difference of the initial sample and final, completely dried powder. The specific water evaporation rate was calculated by the Equation (1):

$$w_{H_2O} = \frac{G_{H_2O}}{A_c} \tag{1}$$

Assuming that the bulk density of the material surrounding the inert particles is an arithmetic mean between the densities of the slurry and the dry powder, it is possible to estimate the thickness of the film surrounding the inert particles.

The Equations (2) and (3) used to this aim are the following [19]:

$$\delta_f = 1000\frac{d_p}{2}\left(\sqrt[3]{1+\frac{h}{100}\frac{\rho_p}{\rho_f}}-1\right) \tag{2}$$

where

$$h = 100\frac{\text{Mass of the coating}}{\text{Mass of the coated particles}} \tag{3}$$

Figure 3 illustrates a coated particle with a film of $NaHCO_3$ slurry, which has a thickness denoted as δ_f.

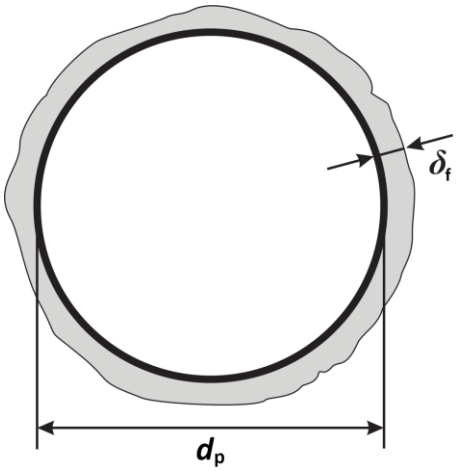

Figure 3. Illustration of a coated inert glass particle

The material hold-up can be also expressed as the mass of the product in contained the bed divided by the unit area of inert particles, kg m^{-2}, φ_p:

$$\varphi_p = \frac{M_{bed}h}{100A_p} \tag{4}$$

All experiments were performed in triplicate and the average values of these measurements are presented in the study.

3. RESULTS AND DISCUSSION

3. 1. General parameters of $NaHCO_3$ slurry drying in the experimental fluidized bed of inert particles

Product moisture content as a function of the drying temperature T_{ge} is shown in Figure 4 for all performed experiments. As expected, the dried powder moisture content decreases with the increase in the bed temperature and it was in the interval from 3 to 30 wt.%. The lowest values were achieved for T_{ge} = 120°C, which is the highest drying temperature used. The lower moisture content of the product at higher drying temperatures (T_{ge}) is explained by the

fact that the driving drying force (ΔT) is lower and therefore the mass flow of the suspension is also lower (*i.e.* the amount of water introduced into the drying column is lower), which affects the final moisture content in the product.

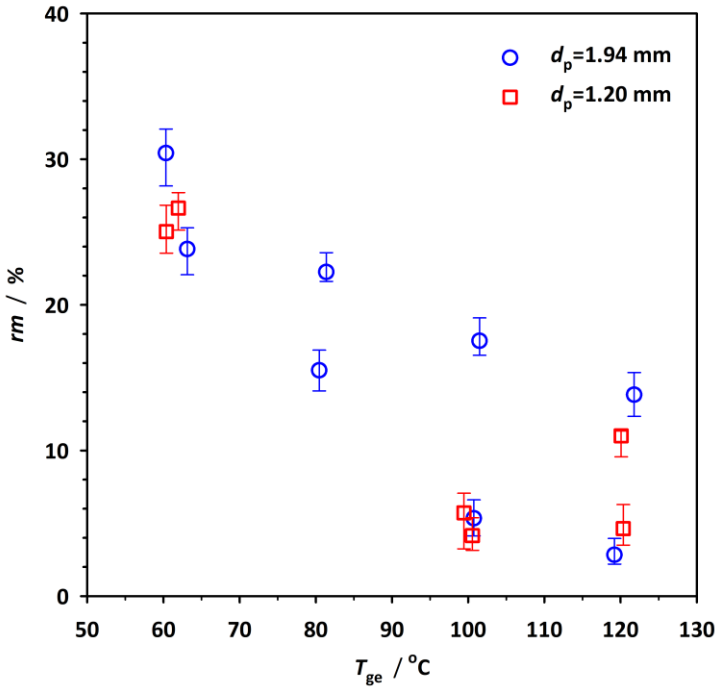

Figure 4. Product moisture content as a function of drying temperature T_{ge} for the two inert particle types used

Specific water evaporation rate ($kg_{H_2O}\ m^{-2}\ h^{-1}$) was calculated according to the Equation (1) as the mass of evaporated water per unit of cross-sectional area and time. Dependence of this parameter on the drying temperature T_{ge} at constant inlet air temperature T_{gi} is shown in Figure 5, for all experimental runs. As can be seen, the specific water evaporation rate is in the range from 190 to 420 kg m^{-2} h^{-1} for both types of inert particles used without visible influence of the particle type.

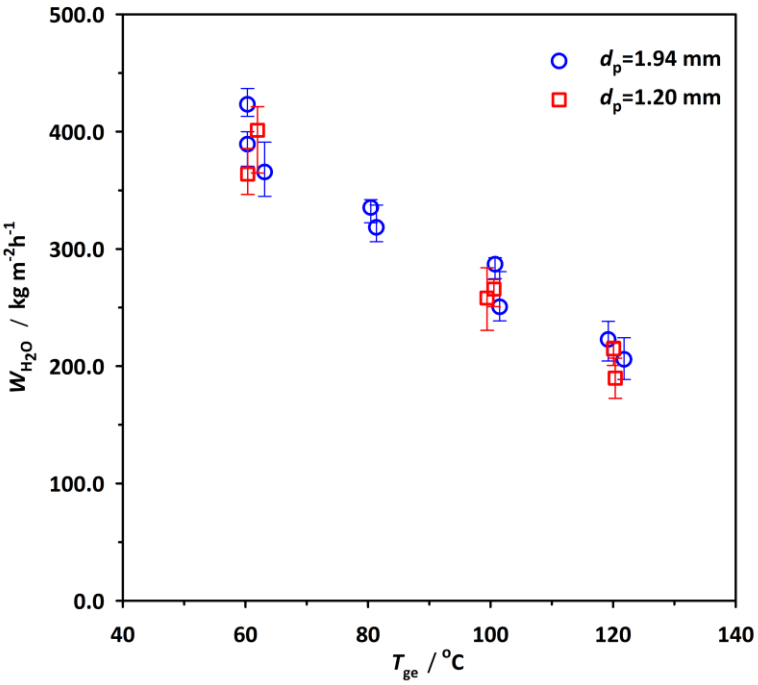

Figure 5. Specific water evaporation rate as a function of drying temperature T_{ge} for the two inert particle types used

3. 2. Material holdup analysis

For each experimental run shown in Table 2, dynamics of the film formation on surfaces of the inert particles were experimentally investigated. In all of the runs, the inlet air temperature was set to T_{gi} = 200 °C, while the outlet temperatures varied in the range T_{ge} = 60 to 120 °C.

Figure 6 shows the film thickness on inert particles A (d_p=1.94 mm) as a function of time, for four different ΔT and for both slurry concentrations.

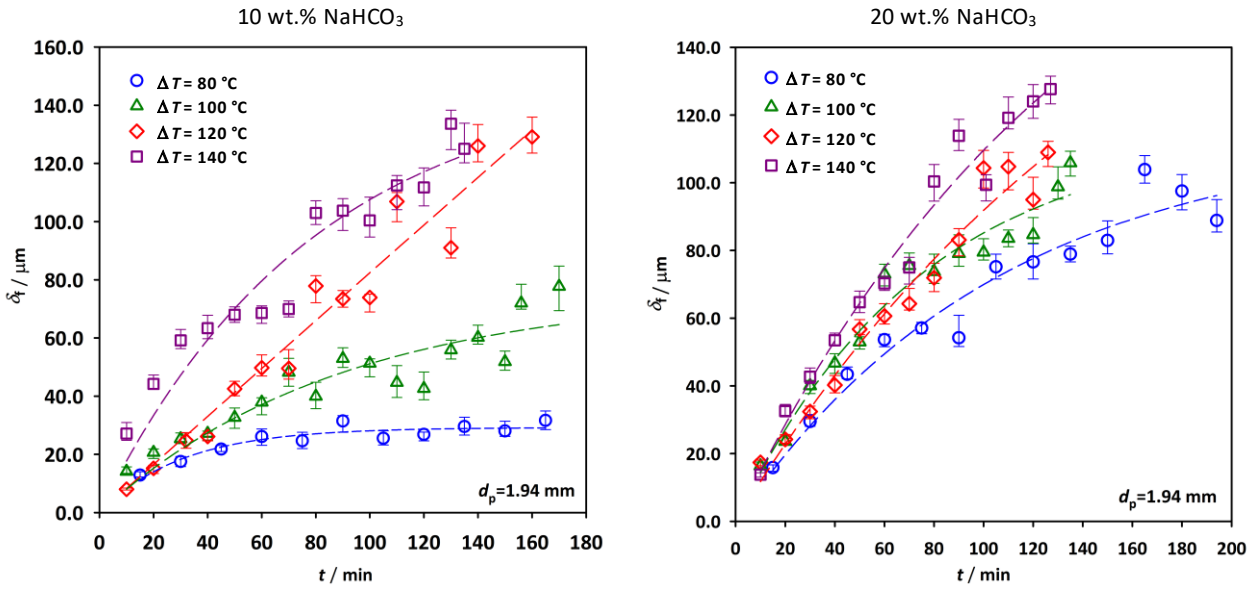

Figure 6. Dependence of the film thickness δ_f on drying time for inert particles A (d_p = 1.94 mm) (symbols; experimental data, lines: exponential model, Equation. (5) predictions)

As it can be seen in Figure 6, the film thickness on inert particles gradually increased with time. It is also evident that with the increase in ΔT, the film thickness increases more rapidly. During drying of the 10 wt.% slurry at ΔT = 80 °C, the film thickness increased from 15 to 22 μm during the time of 180 min, while at ΔT = 140 °C, the increase in film thickness is larger: for the same time of 180 min, the film thickness increased from 24 to 130 μm.

The greater increase in the film thickness with increasing T can be explained by the fact that the mass flow of slurry to be dried increases with higher ΔT, therefore, a larger amount of $NaHCO_3$ comes into the contact with surfaces of the inert particles.

Therefore, due to the larger mass flow of the slurry, a larger amount of $NaHCO_3$ is introduced into the layer of inert particles. Figure 6b shows dependence of the film thickness on drying time for 20 wt.% $NaHCO_3$ slurry. Due to the larger amount of $NaHCO_3$, a greater increase in the film thickness is noticeable, and regarding all experiments performed, the maximal film thickness of $\delta_f \approx$ 90 to 130 μm is reached faster compared to the experiment with 10 wt.% $NaHCO_3$. At ΔT = 8 °C, the film thickness increases from 15 to 25 μm during a time period of about 180 min for 10 wt.% slurry, while under the same conditions for 20 wt.% slurry, the film thickness increases to about 100 μm.

Analysis of the obtained results and dependences of the film thickness δ_f on drying time leads to the conclusion that the film thickness increases exponentially with time and can be described by a two-parameter equation:

$$\delta_f = a(1-e^{-bt}) \quad (5)$$

The results were adjusted to show the trend of growth and changes in the film thickness over time during the drying process. Figure 6 shows that the proposed two-parameter equation represents the experimental data well in all cases except for 10 wt.% $NaHCO_3$ at 120 °C, in which case the film thickness increases linearly. This can be explained by various reasons, such as the fact that under certain conditions the adhesiveness (stickiness) of sodium bicarbonate increases, which influences the drying process and the drying kinetics. The concentration of $NaHCO_3$ can also influence the viscosity and surface tension of the slurry, resulting in its unique impact on the drying process. Also, there could be experimental

errors or deviations in data collection for this experiment that led to the apparent deviation. Further experimental investigations and mathematical modeling are planned for future work in which this finding will be investigated in detail.

Figure 7 shows the film thickness on the inert particles as a function of time, for inert particles B (d_p = 1.20 mm) for three different ΔT and for both slurry concentrations.

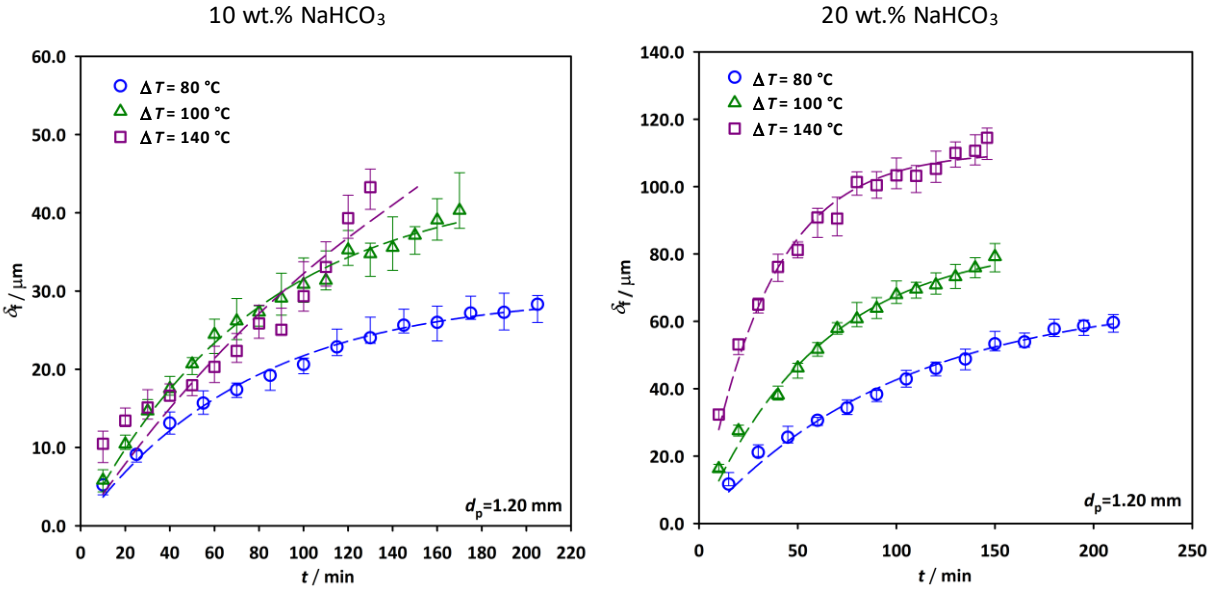

Figure 7. Dependence of film thickness δ_f from drying time for d_p = 1.20 mm (symbols: experimental data, line: exponential model, Equation (5) predictions)

A similar dependence can be observed for 1.2 mm particles: with an increase in the slurry flow rate, *i.e.*, at higher ΔT values, the rate of film thickness formation increases over time. During drying of the 10 wt.% slurry at ΔT = 80 °C, the film thickness increases from 5 to 28 μm during a time period of 205 min, while at ΔT = 140 °C, the increase in film thickness is larger: for a time period of 130 min, the film thickness increases from 10 to 43 μm. Due to the larger amount of $NaHCO_3$ (20 wt.% $NaHCO_3$ slurry), a greater increase in the film thickness is noticeable, and for all experiments performed, the maximal film thickness of $\delta_f \approx$ 60-115 μm is reached faster compared to the experiments with 10 % w/w $NaHCO_3$. At ΔT = 80 °C, the film thickness increases from 12 to 60 μm during a time of about 210 min for 20 wt.% slurry.

Figure 8 provides the comparison of the material hold-up for slurry concentrations of 10 and 20 wt.%. It can be seen that the hold-up is notably higher for the more concentrated slurry, when the rest of the conditions are the same.

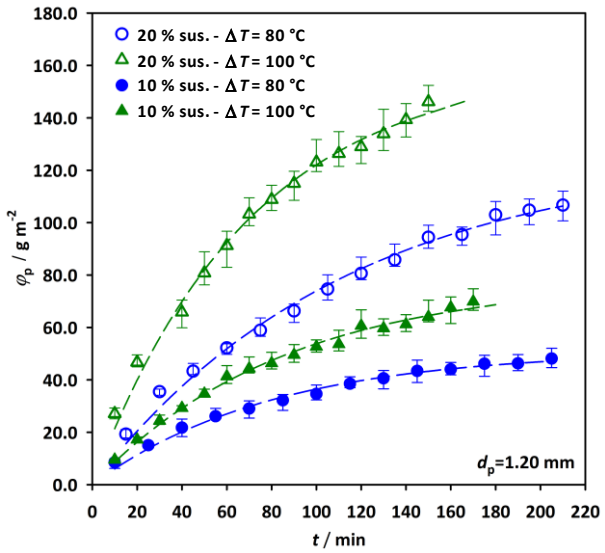

Figure 8. Comparison of the material hold-up for different slurry concentrations

Future research will include additional experimental measurements to investigate the influence of the process parameters on the film thickness and the moisture content in the end-product as well as to derive appropriate mathematical models.

4. CONCLUSIONS

Drying of solutions, suspensions and pastes in a fluidized bed of inert particles is a very effective technique for drying materials whose physical properties are such that the dried material can be easily separated from the particle surface after adhesion to the particle surface. The adhesion of the materials can be expressed numerically by the material hold-up and the film thickness on the surface of the inert particles. Knowing the hold-up of the particular material is very important for process optimization, as it helps determining efficiency of the drying process and the extent of drying that can be achieved in this type of system. In this paper, influences of the process parameters on the material hold-up in the fluidized bed dryer with inert particles for $NaHCO_3$ slurry drying were investigated. It was concluded that there is a strong dependence of the material hold-up on the initial slurry concentration as well as on the drying temperature. The material hold-up increased with the increase in the slurry initial concentration and with the increase in the ΔT. The rate of the material film coating formation is quicker at higher drying temperatures. The product moisture content was in the interval from 3 to 30 %. The lowest values were achieved for T_{ge}=120 °C, which is the highest drying temperature used. The results presented in this paper for $NaHCO_3$ slurry drying have shown that a fluidized bed dryer can be efficiently used for this material, while the established dependences are relevant for development of fluidized bed drying processes for other materials.

5. NOMENCLATURE

Latin symbols

A_c / m^2 - Cross-sectional area of the column at distributor plate
d_p / m - Inert particle diameter
D_c / m - Column diameter (at distributor plate)
G_{dm} / kg s^{-1} - Mass flowrate of dry matter
G_{H_2O} / kg s^{-1} - Water mass flowrate
G_{sus} / kg s^{-1} - Suspension mass flowrate
h / % - Material hold-up
M_{bed} / kg - Mass of the bed
rm / % - Product moisture content
T_{gi} / °C - Inlet air temperature
T_{ge} / °C - Outlet air temperature
T_0 / °C - Ambient temperature
U_{mF} / m s^{-1} - Minimum fluidization velocity at distributor plate
W_{H_2O} / kg m^{-2}s^{-1} - Specific water evaporation rate (G_{H_2O}/A_c)
x / kg kg^{-1} - Water content in the suspension (G_{H_2O}/G_{sus})

Greek symbols

δ_f / m - Material film thickness on inert particles
φ_p / kg m^{-2} - Mass of the product hold-up per inert particle surface
ρ_f / kg m^{-3} - Water density
ρ_p / kg m^{-3} - Particles density

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Zadržavanje materijala na inertnim česticama prilikom sušenja u fluidizovanom sloju

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Izvod

U ovom radu ispitivan je uticaj procesnih parametara na zadržavanje materijala (engl. *hold-up*) u sušnici sa fluidizovanim slojem inertnih čestica. Eksperimenti su izvedeni u pilot postrojenju sa cilindričnom kolonom za sušenje prečnika 0,215 m i visine 1,2 m, uz korišćenje staklenih sfera prečnika 1,20 mm i 1,94 mm kao inertnih čestica. Materijal korišćen za sušenje je bila suspenzija $NaHCO_3$ dve različite koncentracije, 10 i 20 mas.%. Eksperimentalno je ispitana dinamika formiranja sloja materijala na inertnim česticama za četiri različite temperature sušenja, koje su se kretale od 60 do 120 °C, uzimanjem uzoraka obloženih čestica tokom procesa sušenja i merenjem njihove mase sa i bez formiranog filma materijala. Dobijeni rezultati su pokazali da postoji izražena zavisnost zadržavanja materijala od koncentracije suspenzije, kao i od temperature sušenja. Zadržavanje materijala se povećava sa povećanjem koncentracije suspenzije, a takođe i sa povećanjem temperature sušenja. Brzina formiranja filma materijala na inertnim česticama je veća na višim temperaturama sušenja.

Ključne reči: sušenje; suspenzija; praškaste materije; procesni parametri; koncentracija; temperatura