High Efficiency Disperse Dryer - an innovative process for drying of solutions, suspensions and pastes in a fluidized bed of inert particles

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Abstract

In this paper, an innovative fluidized bed dryer with inert particles is presented. The system can be used for drying of solutions, suspensions and pastes in order to obtain a powdered product. The experiments were performed in a pilot-scale dryer with a cylindrical column 0.215 m in diameter and 1.2 mm height, with glass spheres as inert particles. The material used for drying was $CuSO_4$ solution. The effects of operating conditions on the dryer throughput and product quality were investigated. Main performance criteria, *i.e.* specific water evaporation rate, specific heat consumption and specific air consumption, were quantified. Nearly isothermal conditions were found due to thorough mixing of the particles. The energy efficiency of the dryer was also assessed. Simple heat and mass balances predicted the dryer performance quite well.

Keywords: powder; particle size; evaporation rate; specific heat consumption

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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), *etc.* Mujumdar [1] pointed out that numerous new or improved drying technologies are currently at various stages of development. Over 400 dryer types have been cited in the technical literature although only about 50 types are commonly found in practice. The dryer selection is a complex process, which is not entirely scientific but also involves subjective judgment as well as considerable empiricism. It should be noted that pre-drying as well as post-drying stages have important influence on the selection of the appropriate dryer type for a given application. Each type of a dryer has specific characteristics, which make it suitable or unsuitable for specific applications [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]. Independently of the hydrodynamic configuration of a dryer, 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. The extensive introduction of fluidization into

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drying processes resulted from several principal advantages. With respect to the main efficiency criteria, *i.e.* specific water evaporation rate, specific heat consumption and specific air consumption, a fluidized bed dryer with inert particles represents a very attractive alternative to other drying technologies. 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. 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 (Fig. 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 (Fig. 2b). In this case, a more homogenous and stable bed can be obtained by incorporation of a low-speed mechanical mixer. Its role is to additionally prevent formation of large aggregates. 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.

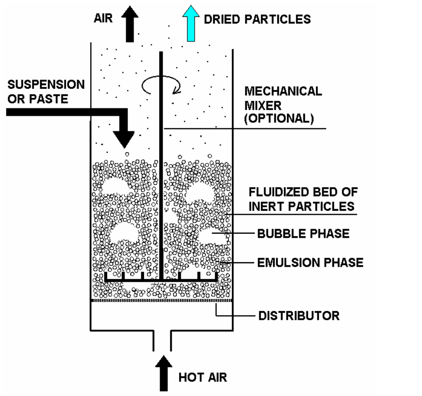

Figure 1. Drying of suspensions in a fluidized bed of inert particles [11] (Reprinted from Drying of suspension and pastes in fluidized bed of inert particles J. Serb. Chem. Soc. 65(12):963–974(2000) with permission of Serbian Chemical Society)

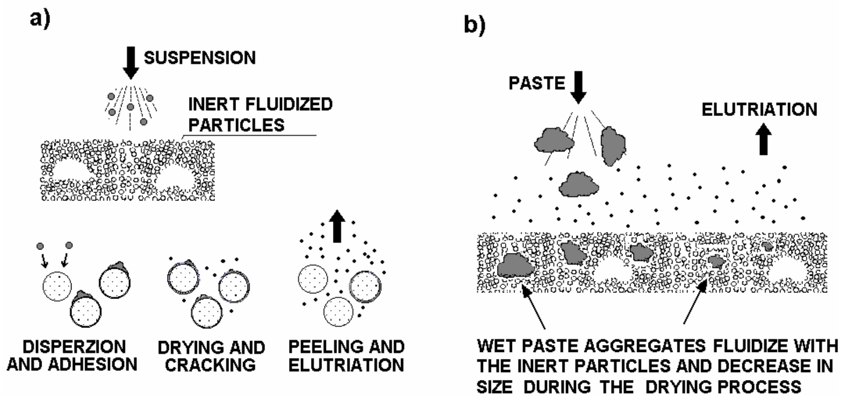

Figure 2. Drying mechanism a fluidized bed with inert particles with a feed: a) suspension, b) paste [11] (Reprinted from Drying of suspension and pastes in fluidized bed of inert particles J. Serb. Chem. Soc. 65(12):963–974(2000) with permission of Serbian Chemical Society)

2. EXPERIMENTAL

Our innovative fluidized bed dryer is schematically shown in Figure 3. The drying chamber is a cylindrical column D_c = 0.215 m *i.d.* and 0.3 m height, connected to a conical section of the dimensions 0.32 m *i.d.* and 0.3 m height. The overall column height is 1.2 m, where the effective column height (above the distributor) is 0.9 m. Different inert particles can be used, *e.g.* glass, alumina and zirconium oxide particles, depending on the type of material that is dried in the system. In the experiments presented in this paper, glass spheres of the mean diameter d_p = $1.94\cdot10^{-3}$ m and density of 2460 kg/m^3 were used. The total mass of inert glass particles was 5.10 kg, the static bed height was 95 mm and the total inert particle surface area was 6.55 m^2. Minimum fluidization velocity for these particles was determined to be U_{mF} = 0.96 m/s at ambient air temperature. The feed material ($CuSO_4$ solution) was directly pumped into the bed at its axis, using a peristaltic pump. The feed outlet is located 0.1 m 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 passes through a packed bed scrubber. 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 with the 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 to the temperature 20 °C above the outlet air temperature. Its role is to prevent overheating of the bed, in the case of the 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 as well as the solution flow rate.

In order to calculate the uncertainty of the experimental measurements, standard deviation was used. Standard deviation represents the measure of the data distribution and was calculated according to the following equation:

$$\mathrm{SD} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(x_i - x_{avg}\right)^2} \tag{1}$$

where x_i is a value in the data set, x_{avg} is the mean of the data set, and N is the number of data points in the population.

The measured variables in our experiments on the basis of which the calculations were made were inlet and outlet air temperature and the solution flow rate. The calculated values of the standard deviations for all of the temperature measurements were between 0.206 and 1.457 for T_{gi}, between 1.169 and 5.450 for T_{ge} and for solution flow rates between 0.224 and 1.257 for all of the experimental runs performed.

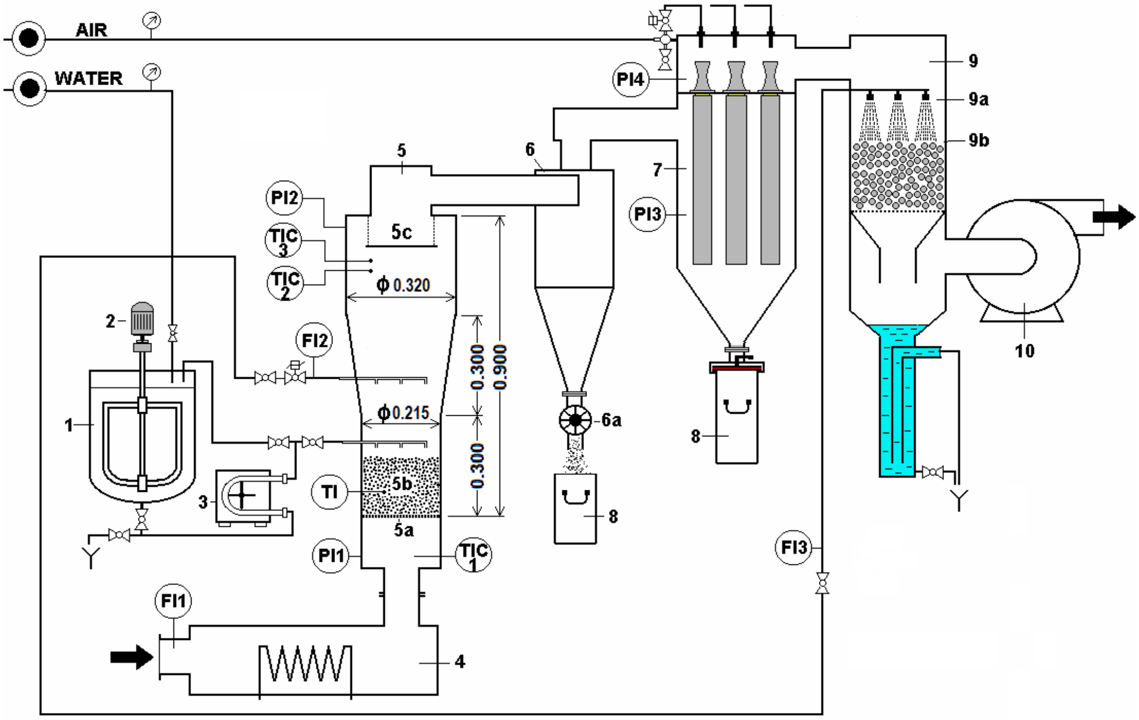

Figure 3. Schematic diagram of the drying system (1 - tank, 2 - agitator, 3 -pump, 4 - air heater, 5 - fluidization column, 5a - distributor, 5b - inert particles, 5c - deflector, 6 - cyclone, 6a - rotary valve, 7 - bag filter, 8 - product containers, 9 - scrubber, 9a - nozzle, 9b - packing, 10 - blower) [11] (Reprinted from Drying of suspension and pastes in fluidized bed of inert particles J. Serb. Chem. Soc. 65(12):963–974(2000) with permission of Serbian Chemical Society)

The presented drying system is designed in order to investigate potential applications and to define optimal process parameters depending on the material that is dried and the quality of the final product.

In this paper, the experimental results obtained for $CuSO_4$ drying are presented. The drying tests were performed continuously. 29 experiments were conducted, at different inlet air temperatures (140, 180, 220, 250 and 280 °C). Due to the intensive mixing during fluidization, drying temperatures were the same as the outlet air temperatures and varied between 60 and 114 °C. $CuSO_4$ solution of 5 % w/w concentration was used in the experiments. Solution flow rates were varied in the range 2.8 - 21.8 kg h^{-1}.

3. RESULTS AND DISCUSSION

In the described fluidized bed dryer, a number of materials were successfully treated, such as fungicides and pesticides (Zineb, Ziram, Propineb, Mangozeb, copper oxy-chloride, copper oxy-sulphate, bordeaux mixture), inorganic compounds (calcium carbonate, calcium sulphate, cobalt carbonate, electrolytic copper, copper sulphate, sodium chloride), complex compounds (organo-bentonite) and waste water treatment sludge. The experimental trials of drying several organic and biological materials such as calcium stearate, tartaric acid, brewery yeast, soya milk and their mixtures, liposome, tomato pulp, raw eggs, starch, were unsuccessful because of the powder characteristics.

Also, the possibility of drying municipal waste water treatment sludge was investigated in this system. Benefits of drying this sludge can be seen in several aspects: the dried sludge can be stored for longer periods of time and further used as an organic fertilizer, it can be a source of useful (active) microorganisms that can be reused in waste water treatment. Drying also enables incineration or co-incineration of sludge. Sludge drying process reduces mass and volume of the product, making its storage, transport, packaging and retail easier [2-4].

In this paper, the experimental results obtained for $CuSO_4$ drying are presented. For all runs, a 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. Subsequently, the outlet air temperature was maintained constant since the TIC2 controls the feeding device. Steady state was reached after several minutes since the inlet air temperature had reached the set value TIC1. As the fluidized bed is well mixed, the drying temperature was the same as the outlet air temperature. The system was very stable, *i.e.* during operation the outlet air temperature variations (ΔT_{ge}) were less than 5 °C, as can be seen from Figure 4 in which the error bars are also presented. The calculated standard deviation for T_{gi} in this case is SD (T_{gi})=0.2926, and for T_{ge} is SD (T_{ge})= 1.1677.

Figure 5 presents the specific water evaporation rate (kg_{H_2O}/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 601 $kg_{H_2O}m^{-2}h^{-1}$ at the superficial air velocity (calculated at 20 °C) of U_0 = 1.91 ms^{-1} and at the inlet air temperature of T_{gi} = 279 °C and the outlet air temperature of T_{ge} = 71°C.

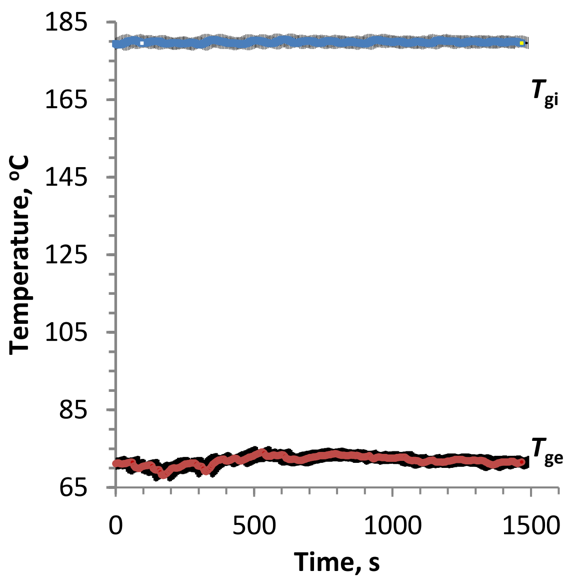

Figure 4. Example of the recorded temperature profile (feed $CuSO_4$, suspension mass flowrate G_{SUS} = 11.8 kg/h, water content in the suspension, x=0.5, inlet air temperature, T_{gi}=180 °C, outlet air temperature, T_{ge}= 72 °C), SD(T_{gi})=0.2926 and SD(T_{ge})=1.1677

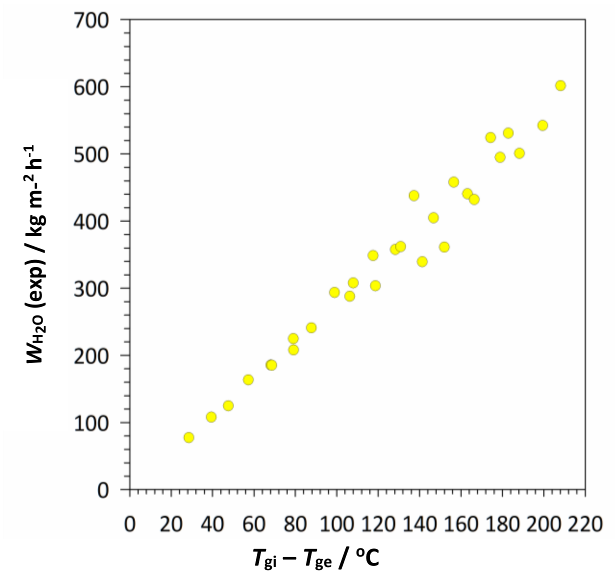

Figure 5. Specific water evaporation rate for a $CuSO_4$ solution as a function of the temperature difference between the inlet and outlet air temperatures

Figure 6 shows the specific heat consumption of the process. This parameter was calculated on the basis of temperature differences $\Delta T_1 = T_{gi} - T_{ge}$ and $\Delta T_2 = T_{gi} - T_0$, where T_0 represents the ambient temperature. As can be seen, the specific heat consumption q (based on ΔT_1) is approximately independent of drying conditions and it is slightly above the latent heat of water evaporation. The specific consumption q' based on ΔT_2 decreases as the temperature difference increases, indicating that the overall system efficiency increases with the increase in the inlet air temperature.

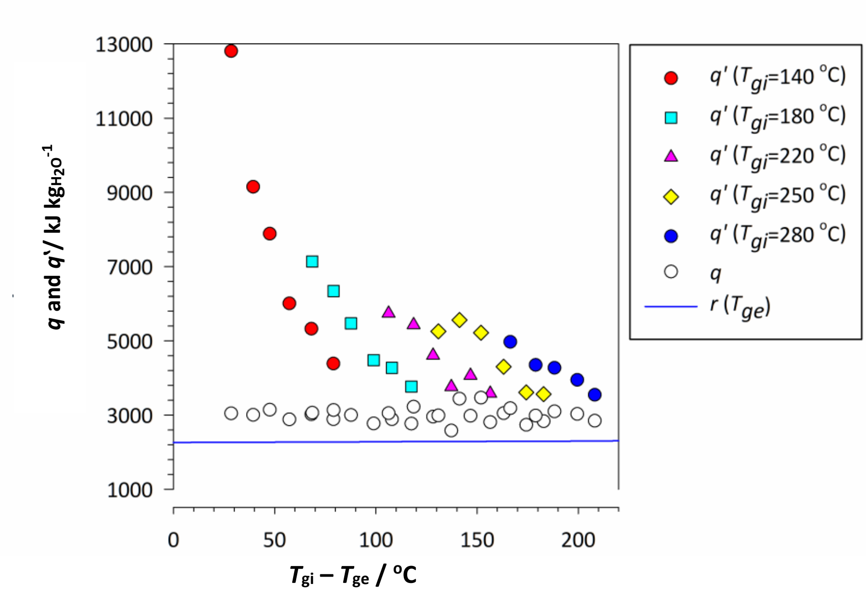

Figure 6. Specific heat consumption values q and q` as functions of the inlet and outlet air temperature difference T_{gi}-T_{ge}*, at different inlet air temperatures,* T_{gi}*; blue line presents the latent heat of evaporation, r (feed* $CuSO_4$ *solution)*

Figure 7 shows the specific air consumption per mass of evaporated water (kg $kg_{H_2O}^{-1}$) as a function of the temperature difference, T_{gi}-T_{ge}. It can be seen that the data follows the same trend as the specific heat consumption shown in Figure 6.

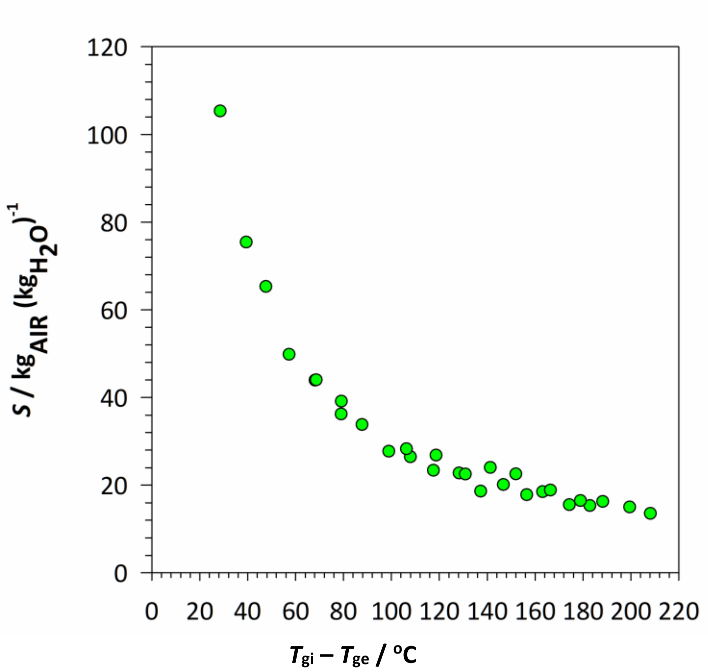

Figure 7. Specific air consumption as a function of the inlet and outlet air temperature difference T_{gi}-T_{ge}

Table 1 presents data for a typical drying run.

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.

Table 1. Typical drying run ($CuSO_4$ solution, water content in the suspension, x = 0.95 $kg_{H2O}\ kg_{SUS}^{-1}$)

Air flowrate (20 °C)	m^3h^{-1}	V_0	250
Superficial air velocity (20 °C)	ms^{-1}	U_0	1.91
Inlet air temperature	°C	T_{gi}	280.79
Exit air temperature	°C	T_{ge}	101.86
Suspension flowrate	$kg_{sus}h^{-1}$	G_{sus}	18.91
Water flowrate (in solution)	$kg_{H2O}h^{-1}$	G_{H2O}	17.97
Dry mater flowrate (in solution)	$kg_{dm}h^{-1}$	G_{dm}	0.95
Specific water evaporation rate	$kg_{H2O}\ m^{-2}h^{-1}$	W_{H2O}	495
Specific air consumption	$kg\ kg_{H2O}^{-1}$	S	16.47
Specific heat consumption (based on T_{gi}-T_{ge})	$kJ\ kg_{H2O}^{-1}$	q	2984
Specific heat consumption (based on T_{gi}-T_0)	$kJ\ kg_{H2O}^{-1}$	q'	4349
Water content in the product	%	s	5.95

Of all the mentioned parameters, the most commonly encountered in the technical literature is the thermal efficiency [1,2,12]. 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:

$$\eta'_T = \frac{(T_{gi}-T_{ge})}{(T_{gi}-T_p)},\quad or\quad \eta''_T = \frac{(T_{gi}-T_{ge})}{(T_{gi}-T_{wb})},\quad or\quad \eta_T = \frac{(T_{gi}-T_{ge})}{(T_{gi}-T_0)} \tag{2}$$

In Figure 8 the thermal efficiency, η_T, calculated in relation to the ambient temperature according to the Eq. (2) is shown for different inlet air temperatures. As can be seen, the thermal efficiencies are in the interval η_T = 0.24÷0.80 in our system for all the performed experiments, 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) [12].

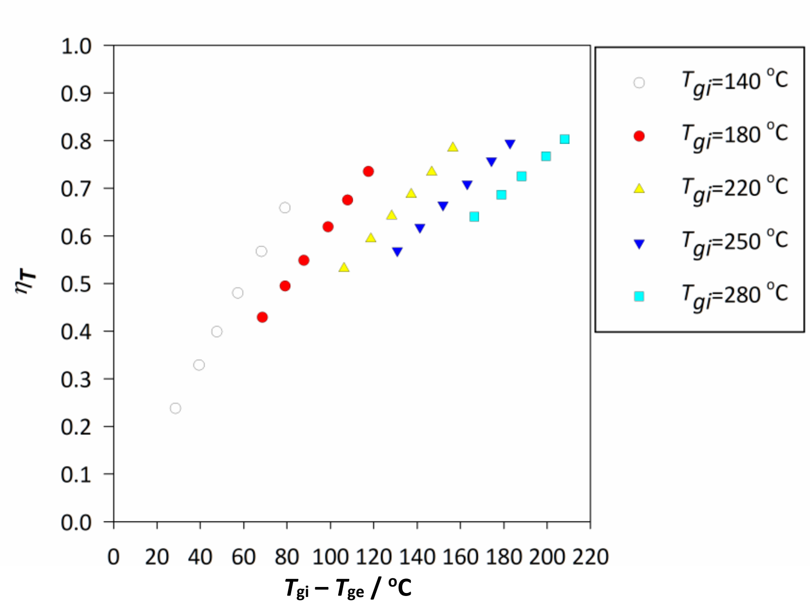

Figure 8. Thermal efficiency (feed $CuSO_4$ solution) as a function of the temperature difference between the inlet and outlet air temperatures for different inlet temperatures

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.

3. 1. Heat and mass balances

Theoretically, water evaporation capacity can be determined from the overall heat balance:

$$G_v c_v/T_{gi} - T_{ge}) = G_{dm}c_{dm}(T_{ge} - T_0) + G_{H2O}\,[c_{H2O}\,(T_{ge} - T_0) + r_{H2O}] + Q_g \tag{3}$$

where G_v – is the air mass flowrate, G_{dm} – the mass flowrate of dry matter, G_{H_2O} – the water mass flowrate, r_{H2O} – the latent heat of water evaporation, c_v - specific heat of air, c_{dm} - specific heat of dry product and Q_g - heat losses.
Since the mass flow of the suspension, G_{sus} is:

$$G_{sus} = G_{dm} + G_{H_2O} \tag{4}$$

and if water content is defined as $x = G_{H_2O} / G_{sus}$ it follows that $G_{dm} = (1 - x)G_{sus} = [(1 - x)/x)]\, G_{H_2O}$.

By using these relationships, Eq. (3) becomes

$$W_{H_2O} = \frac{G_{H_2O}}{A_c} = \frac{1}{A_c}\cdot\frac{G_v c_v\left(T_{gi}-T_{ge}\right)-Q_g}{\left[(1\text{-x})/x\right]c_{dm}\left(T_{ge}-T_0\right)+c_{H_2O}\left(T_{ge}-T_0\right)+r_{H_2O}} \tag{5}$$

where W_{H2O} is the specific water evaporation rate and A_c is the column cross-sectional area.

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}). Since the outlet air temperature (T_{ge}) is selected according to the thermal stability of the drying material and desired residual moisture content, Eq. (5) provides a simple relationship between the inlet air temperature (T_{gi}) and the specific water evaporation rate (W_{H_2O}).

A comparison between experimental and calculated values of W_{H_2O}, by using an estimated value of $c_{dm} \approx 0.85$ kJ kg^{-1}°C^{-1}, is shown in Figure 9. The mean absolute deviation between the experimental and calculated values is 5.8 %, 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.

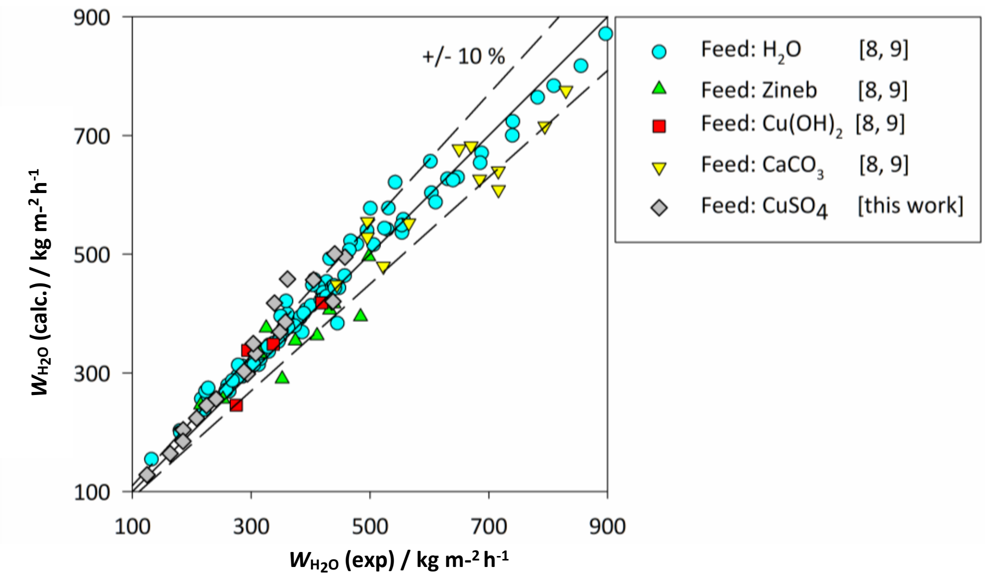

Figure 9. Comparison of the experimental and calculated values of the specific water evaporation rate.

Application of the fluidized bed dryer at the industrial level would lead to significant savings compared to, *e.g.* the conventionally used tunnel dryer chamber. The effective surface of the fluidization column is about 700 times smaller than the required drying trays area for the same capacity. In comparison to the tunnel dryer with trays energy savings of at least 50 % can be achieved. By introducing a high-efficiency dispersion dryer in the production line, due to the energy efficiency of the drying process, large energy savings can be achieved, so the plant would pay off after 2 - 3 years only at the expense of energy savings in comparison to the most commonly used conventional tunnel dryers. Application of the presented technology would enable realization of a plant of significantly smaller dimensions as compared to other types of devices with the same evaporation capacity. A relative comparison of sizes of different dryers with the fluidized bed dryer is illustrated in Figure 10, *i.e*. for suspension with 65 % water content and for capacity of 8 t of dry powdered product per day, it is required: the tunnel dryer with 240 trays 2x1 m in size, spray dryer of 7 m in diameter and fluidized bed dryer of 0.8 m in diameter.

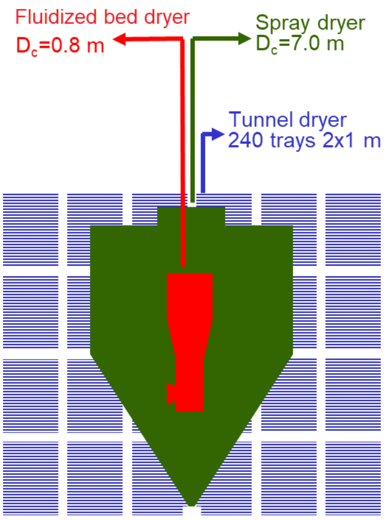

Figure 10. Comparison of different drying systems for the same evaporation capacity

4. CONCLUSIONS

Drying of solutions, suspensions and pastes in a fluidized bed of inert particles is a simple and very effective technique for all materials that do not adhere to the inert particles. This drying concept has some important advantages compared to other drying systems, such as: higher capacity per unit volume of the dryer, lower energy consumption and a lower specific air consumption. The high drying efficiency results from the large contact area and the large temperature difference between the inlet and outlet air. Rapid mixing of the particles leads to nearly isothermal conditions throughout the bed. A simple mathematical model based on the overall heat balance predicts the dryer performance quite well. In our experiment's solutions, suspensions and very dense pastes were successfully treated. The results presented in this paper for $CuSO_4$ solution drying have shown that fluidized bed dryer can efficiently be used for this material.

5. NOMENCLATURE

Latin symbols

A_c / m^2 - Cross-sectional area of the column at distributor plate
c_{dm} / kJ kg^{-1} K^{-1} - Specific heat of dry matter
c_{H_2O} / kJ kg^{-1} K^{-1} - Specific heat of water
c_v / kJ kg^{-1} K^{-1} - Specific heat of air
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
G_v / kg s^{-1} - Air mass flowrate
N - Number of data points in the population

Q / kJ $kg_{H_2O}^{-1}$ - Specific heat consumption, based on T_{gi}-T_{ge}
q' / kJ $kg_{H_2O}^{-1}$ -Specific heat consumption, based on T_{gi}-T_0
Q_g / kJ s^{-1} - Heat losses
r_{H2O} / kJ $kg_{H_2O}^{-1}$ - Latent heat of water evaporation
s / % - Product moisture content
S / kg_{AIR} $kg_{H_2O}^{-1}$ - Specific air consumption (G_v/G_{H_2O})
SD - Standard deviation
T_{gi} / °C - Inlet air temperature
T_{ge} / °C - Outlet air temperature
T_0 / °C - Ambient temperature
T_{wb} / °C - Wet bulb temperature
U_0 / m s^{-1} - Superficial fluid velocity at distributor plate (at T_0)
U_{mF} / m s^{-1} - Minimum fluidization velocity at distributor plate (at T_0)
V_0 / m^3 s^{-1} - Air flowrate (at T_0)
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})
x_i - Value in the data set
x_{avg} - Mean of the data set

Greek symbols

η_T - Thermal efficiency in relation to T_0
η'_T - Thermal efficiency to the surface particles temperature T_p
η''_T - Thermal efficiency in relation to T_{wb}

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SAŽETAK

Visokoefikasni disperzni sušionik – Inovativni proces sušenja rastvora, suspenzija i pasti u fluidizovanom sloju inertnih čestica

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(Stručni rad)

U ovom radu je predstavljen inovativni sušionik sa fluidizovanim slojem inertnih čestica. Prikazani sistem može da se koristi za sušenje rastvora, suspenzija i pasti u cilju dobijanja praškastog produkta. Eksperimenti su rađeni na pilot postrojenju čiji je centralni deo cilindrična kolona prečnika 215 mm i visine 1200 mm. Korišćene su staklene sfere kao inertne čestice. U radu je prikazano sušenje rastvora $CuSO_4$. Ispitivan je uticaj operativnih uslova na performanse sistema za sušenje, kao i na kvalitet praškastog produkta. Kvantifikovani su glavni parametri koji opisuju performanse sušionika, kao što su specifična brzina isparavanja, specifična potrošnja toplote i specifična potrošnja vazduha. Usled intenzivnog mešanja u fluidizovanom sloju postižu se približno izotermni uslovi sušenja. Izvršena je procena energetske efikasnosti sušenja. Jednostavni bilansi prenosa mase i toplote adekvatno predviđaju radni režim sistema za sušenje.

Ključne reči: prah; veličina čestica; specifična brzina isparavanja; specifična potrošnja vazduha