Chemical Engineering & Processing: Process Intensification 130 (2018) 1–10

Contents lists available at ScienceDirect

Chemical Engineering & Processing: Process Intensification

journal homepage: www.elsevier.com/locate/cep

Analysis of the energy performance of a modified mechanically spouted bed applied in the drying of alumina and skimmed milk

R.C. Brito[a], R.C. Sousa[b], R. Béttega[a], F.B. Freire[a], J.T. Freire[a,*]

[a] Federal University of São Carlos, Department of Chemical Engineering, Rod. Washington Luiz – Km 235, P.O. Box 676, 13565-905, São Carlos, SP, Brazil
[b] Federal University of Espírito Santo, Department of Rural Engineering, Campus de Alegre, Alto Universitário, s/n, 29500-000, Guararema, Alegre, ES, Brazil

ARTICLE INFO

Keywords:
Modified mechanically spouted bed
Drying efficiency
Energy consumption
Alumina
Skimmed milk

ABSTRACT

Several spouted bed configurations have been proposed in order to overcome the limitations and disadvantages of the conventional spouted bed (CSB). This paper evaluates the performance of a modified mechanically spouted bed (MMSB) fitted with a helical screw, which was applied in the drying processes of alumina and skimmed milk. In this equipment, the cyclic movement of the solid phase was promoted by the screw and the air was supplied perpendicularly, following the CSB design. The main objective of this study was to analyze the energy performance of the MMSB. The results showed that the MMSB provided a drying process under stable conditions at air velocities lower than the minimum spout velocity, due to inclusion of the helical screw, leading to greater energy efficiency and lower energy consumption.

1. Introduction

The spouted bed offers several useful features and is consequently used in many physical and chemical processes [1–7]. This equipment provides elevated heat and mass transfer rates, due to the high degree of mixing between the phases and the high recirculation rate of solids in the bed. However, despite these advantages, a number of difficulties restrict the use of the spouted bed on an industrial scale. Among the main limitations are low energy efficiency and high air velocity required to establish the spout regime [8–10]. Adequate heat and mass transfer during the drying process in a conventional spouted bed (CSB) can only be obtained using a narrow range of air velocities that ensure maintenance of satisfactory fluid dynamics characteristics. This can result in an excessive supply of energy, without necessarily achieving the optimum drying conditions. In addition, the CSB requires a high pressure drop at start-up, in order to establish the spout. These peculiarities of the CSB, together with the inherent energy issues of convective dryers, lead to poor energy performance [11,12].

Different modifications and settings have been proposed to overcome such limitations and disadvantages. One of these, known as the mechanically spouted bed (MSB), was proposed by researchers at the Research Institute of Hungary and was patented in around 1976. This configuration features a vertical unenclosed screw located in the center axis of the equipment, corresponding to the region of the spout. In this configuration, the air feed is through tangential openings in the conical base of the dryer, with the screw promoting the characteristic cyclic movement of particles in the spouted regime [12,13].

There have been few studies reported in the literature investigating this type of layout [12–19]. Kudra et al. [14] evaluated the MSB for paste drying and found that the operation was possible under conditions below the minimum fluidization, consequently reducing the energy consumption. Szalay et al. [19] employed the MSB for the drying of brewery yeast with inert particles, defining the optimum operating conditions to be used in scaling-up calculations. The MSB designed met the requirements in terms of the processing capacity and product quality. Pallai-Varsányi et al. [18] investigated application of the MSB in the drying of three different materials: aluminum hydroxide-oxide suspensions, tomato paste, and protein solutions. The equipment successfully dried these materials, complying with the relevant operational and quality requirements.

In recent work, Sousa [20] developed a modified mechanically spouted bed (MMSB) with a helical screw. In this equipment, the air was supplied perpendicularly through the lower hole of the conical base, as in the CSB. Therefore, both settings (conventional and mechanically spouted) could be used in similar experimental units employed for drying pastes and particulate materials. Only a few recent studies can be found in the literature concerning applications of the MSB and MMSB in the drying of particulate solids. Furthermore, there is a lack of analysis in relation to the energy performance of such equipment. Considering the characteristics and possible applications of the MMSB, an analysis that focuses not only on energy consumption, but also on energy efficiency and the main variables that can influence

* Corresponding author.
E-mail address: freire@ufscar.br (J.T. Freire).

https://doi.org/10.1016/j.cep.2018.05.014
Received 16 November 2017; Received in revised form 30 April 2018; Accepted 23 May 2018
Available online 26 May 2018

Nomenclature

C	Initial water mass fraction [kg kg^{-1}]
c_p	Specific heat of air [kJ kg^{-1} K^{-1}]
EE	Energy efficiency [-]
F	Paste feed rate [mL min^{-1}]
g	Gravitational acceleration [m s^{-2}]
Gr	Grashof number [-]
$\Delta H_{v,s}$	Latent heat of free water vaporization [kJ kg^{-1}]
$\dot{m}$	Mass flow rate of air [kg s^{-1}]
m_{ds}	Mass of dry solids [kg]
N	Screw rotation [rpm]
Nu	Nusselt number [-]
ΔP	Pressure drop [Pa]
ΔP_m	Maximum pressure drop [Pa]
ΔP_s	Stable spout pressure drop [Pa]
Q	Thermal energy supplied [kJ s^{-1}]
Q_w	Energy required to evaporate the water [kJ]
SEC	Specific energy consumption [kJ kg^{-1}]
t	Time [s]
T	Temperature [K]
T_a	Ambient temperature [K]
T_d	Drying air temperature [K]
T_w	Wall temperature [K]
u_{mj}	Minimum spout velocity [m s^{-1}]
Δv	Variation of air velocity [m s^{-1}]
W_m	Mechanical energy [kJ s^{-1}]
W_s	Shaft work [kJ s^{-1}]
x^*	Characteristic length of the vertical frustum of the cone [m]
X^*	Dimensionless moisture [-]
$\overline{X}$	Mean moisture (dry basis) [kg kg^{-1}]
$\overline{X_i}$	Mean initial moisture (dry basis) [kg kg^{-1}]
X_{eq}	Moisture at dynamic equilibrium (dry basis) [kg kg^{-1}]

Subscripts

i	Initial
s	Solid
t	Time

Greek symbols

α	Cone angle [degrees]
β	Coefficient of thermal expansion [K^{-1}]
ρ	Specific mass of air [kg m^{-3}]
ρ_p	Specific mass of paste [kg m^{-3}]
ν	Kinematic viscosity [m^2 s^{-1}]
τ	Torque [kN m]

the energy performance, is of great importance.

Given the above background, the objective of this study was to analyze the energy performance of the MMSB, with assessment of the influence of the operating conditions on the energy parameters, as well as to provide an overview of the application of the MMSB in the drying of alumina and skimmed milk. In addition, an analysis was made of the application of the MMSB and the CSB in the drying of alumina under similar operational conditions, in order to confirm the feasibility of the proposed modification.

2. Materials and methods

2.1. Materials

Two different types of material were used in the drying experiments using the MMSB: particulate solids and pastes. The experiments with particulate solids employed 4 kg of activated F-200 alumina particles with mean diameter of 3.42 mm (donated by Alcoa Alumina S.A.). Before each drying process, the alumina particles were saturated with water for a period of 48 h.

Skimmed milk with initial water mass fraction of 0.92 ± 0.01 (wet basis) and specific mass of 1032.83 kg/m^3 was used for the experiments with pastes. The skimmed milk was purchased in a local supermarket and no additional preparation was performed. The composition of the skimmed milk provided by the manufacturer (Parmalat), per 200 mL, was 6.0 g of protein, 130 mg of sodium, and 210 mg of calcium. In the skimmed milk drying experiments, 3 kg of glass spheres with diameter of 3.20 mm were used as the inert particles.

2.2. Equipment

The fluid dynamics and drying experiments were carried out using the experimental unit shown schematically in Fig. 1.

A 7.5 HP blower with an adjustable bypass system was used to provide the required air flow, which was measured with a Venturi meter. The air flowed through a heater with three resistances controlled by a temperature controller. The spouted bed unit was composed of a stainless steel cylindrical vessel (87 cm height, 30 cm diameter), with identical 60° conical sections (23 cm height) at the top and bottom. The skimmed milk was injected into the spouted bed by a double fluid feeder mounted axially in the central region of the cylindrical column base.

Unlike the system described by Szentmarjay and Pallai [12], the air entered perpendicularly to the conical base. This design was used in order to allow the use of both conventional (CSB) and mechanically spouted (MMSB) modes in a single experimental unit. Fig. 2 illustrates the helical screw employed in the MMSB, which was inserted at the top of the equipment.

The helical screw consisted of a shaft 0.01 m in diameter and 1.30 m in length, together with a 0.70 m spiral with diameter of 0.02 m. A

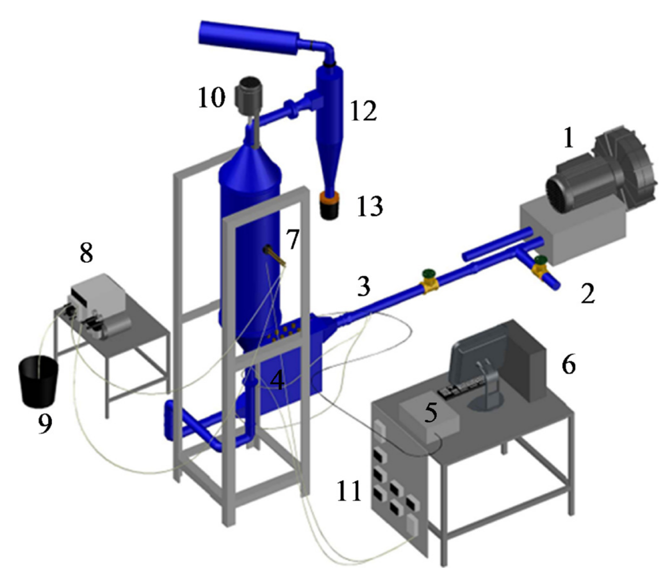

Fig. 1. Components of the experimental unit used for the drying experiments: (1) blower; (2) bypass system; (3) Venturi flow meter; (4) heater; (5) temperature controller; (6) data acquisition system and microcomputer; (7) drying chamber; (8) peristaltic pump; (9) feed reservoir; (10) screw motor; (11) pressure transducers; (12) cyclone; (13) sample collector.