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Simulation and validation of a model for a batch wall heated fluidized bed dryer

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ABSTRACT

Drying of wet particulate solids is carried out in a novel way in a wall heated fluidized bed dryer. The experimental data shows that drying occurs effectively. The temperature variation with respect to time reveals that there is evaporative cooling occurring in the solids. Initially, there is lowering of temperature, then an increase is noticed and finally it reaches steady state. This phenomenon of wall heated drying is modelled first by percolation model by taking radial average of temperature of air, temperature of solids and moisture content of solids but accounting for axial variation along the height of the cylindrical fluidized bed. The drying rate is considered to depend on the local temperature of the solids in the fluidized bed. This procedure produced three coupled partial differential equations: one for temperature of air, second for temperature of solids and third for moisture content of solids. The axial convective heat transport equation and drying rate equation are solved using an explicit Euler numerical method. Well-mixed (CSTR) model and CSTRs-in-series model are also presented to account for recirculations in the bubbling regime of fluidization. The simulation results of CSTRs-in-series model show a good agreement with experimental data for temperature and moisture variation. Especially, the evaporative cooling phenomenon is captured successfully through simulation.

1. Introduction

Fluidized bed dryers (FBD) are widely used in chemical, pharmaceutical, food and mineral process industries for drying of moist solids. A classification is done to delineate the fluidization regimes and flow patterns in fluidized beds [1]. Fluidized bed dryers have many advantages compared to other dryers such as tray dryers and rotary vacuum dryer [2]. The fluidized bed dryers are mainly adopted to enhance the drying rates in drying operation. The advantages with the fluidized bed dryers are extremely high surface area of contact between gas and solid per unit bed volume, high relative velocities between the gas and the dispersed solid phase, high levels of intermixing of the solids phase, frequent particle – particle and particle – wall collisions resulting in higher heat and mass transfer rates [3].

Temple and Boxtel [4] have developed a model to predict the drying behavior in a three stage fluidized bed dryer for black tea using hot air as a heating medium by assuming continuous stirred tank reactor model to predict the temperature and moisture variation in solids.

Wang and Chen [5] have studied pressure variation along the height with respect to time by numerical modeling. Burgschweiger and Tsotsas [6] have modeled dynamic and steady state continuous fluidized bed drying using hot gas as heating medium by applying the population balance to predict the drying kinetics. The fluidized bed dryer was modeled as a series of continuous stirred tank reactors. Syahrul et al. [7,8] have developed a model to study energy and exergy efficiencies in a fluidized bed dryer for wheat and corn particles using hot air as a heating medium assuming spatial variation of the physical and thermo physical quantities as negligible. Groenewold and Tsotsas [9], have studied effect of immersion of heating element in a fluidized bed dryer. Cooling effect has been observed and drying kinetics variation has been studied due to immersion of heated object. Debaste et al. [10] have studied external and internal mass transfer resistances in yeast drying and a model has been developed assuming fluidized bed dryer as a batch or lumped parameter model to predict the drying behavior. Geldart and Lewis [11] have studied heat transfer from immersed bodies at high temperatures in sand fluidized bed. Silva et al. [12] have studied drying behavior for soya meal in a fluidized bed dryer experimentally and simulation by using Eulerian–Eulerian two fluid model with respect to time variation only.

It can be inferred from above literature that it is a very difficult task to simulate the drying behavior in fluidized bed dryer with respect to temporal and spatial variation of moisture content of solids, solid temperature and air temperature. In the present study, the influence of wall heat source on fluidized bed drying is modeled and simulated by incorporating the variation of temperature of air, solids and moisture content in solids with respect to time and position along the height of the fluidized bed.

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Compared to the above discussed models for hot air FBDs and internally heated FBDs, the present model is novel. The novelty is that, a distributed parameter model is developed for spatial and temporal variation for moisture content of solids, temperature of air and temperature of solids in a wall heated FBD. Since there is availability of high speed computation now-a-days, such coupled ordinary differential equations (ODEs) and partial differential equations (PDEs) could be solved by simple finite difference method in space in combination with Eulerian approach for time unlike the approximations proposed in earlier models [4–6,9–11]. The present detailed modelling approach is described in Section 3.

The advantage of this wall heated fluidized bed dryer (FBD) is that the solids temperature does not increase to a high temperature like in hot air fluidized bed dryer since the inlet air is at room temperature. In the case wall heated FBD, the heat supplied to the wall could be controlled at a desired level. The dried product in hot air fluidized bed dryer is at drying medium temperature and it requires to be cooled to room temperature. Also to heat the air medium high energy consumption is required due to low thermal conductivity of air. Heat is also lost in the transportation of hot air. These drawbacks of hot air FBD may be overcome using wall heated FBD. The evaporative cooling effect is found to keep the solids at a temperature closer to the room temperature or inlet air temperature and at the same time causing a good drying effect. Hence, this type of wall heated FBD is useful for drying of particulate solids which are heat sensitive like the materials produced in pharmaceutical, food and other related industries.

2. Experimental setup and procedure

A schematic diagram of experimental setup is shown in the Fig. 1. Similar experimental setup was used to study wall heated fluidized bed drying of binary solid mixture by Srinivas and Pydi Setty [13]. The atmospheric air from the compressor was sent into the fluidized bed dryer through a rotameter for flow rate measurement. The flow range available on the rotameter is 0–100 kg/h. Heat was supplied to fluidized bed through the electrically heated wall with the inlet air being supplied at room temperature. Solids are generally classified as Geldart C, A, B and D particles based on their size and density [1]. In the present study sand particles of average size 1.2 mm with true density 2500 kg/m^3 have been used for drying studies. The solids used were sand particles of size approximately 1.2 mm which falls under Geldart D type particles. The solids with low initial moisture content are studied. The air was passed through the calming section provided with a pipe of length 80 cm to create fully developed flow before it reaches the distributor plate. Distributor plate used is a perforated plate placed above the calming section with a suitable mesh fixed to it such that sand particles do not fall below. The fluidized bed column height is 40 cm and inner diameter is 8.3 cm. It is surrounded with an electric heater made up of nichrome wire. The height of heating zone is 40 cm. Insulation in the form of glass wool was also provided surrounding the electric heater to minimize heat loss. The power supply is routed through a rheostat. By controlling the rheostat, the heat supply to the column is varied.

Initially, the heater was switched on to allow it to reach a steady state without any solids in the dryer. Then a measured quantity of wet sand with initial moisture content of 0.1 kg water/kg dry sand was added. Then air was passed through it at a measured flow rate to create fluidization [14]. The bed height initially is 0.05 m and expands to a fluidized height of 0.4 m. The minimum fluidization velocity of these sand particles is 0.78 m/s [14]. The wet solids require higher velocity than the dry solids to obtain a sufficiently high fluidization condition. Hence, an air velocity of 2.13 m/s was provided. It results in a bubbling fluidization regime as can be inferred from Geldart flow regime chart [1]. Temperature sensors are provided at various heights along the fluidized bed. The temperatures were recorded as a function of time. In correspondence with time, the samples of sand each of 2 grams were collected from various heights of the column. The collected samples were analyzed to provide data of moisture content in the solids at regular intervals of time. Four temperature sensors (PT 100) with data logging system have been used to measure and record the temperature at different locations at regular interval in the fluidized bed dryer. The tips of the four sensors are located centrally or along the axis of the FBD column. In the model, it is assumed that the radial variation of temperature in the fluidized granular bed is negligible due to large L/D or aspect ratio of the column and also due to smaller diameter of the column.

Fig. 2 presents the experimental results of bed temperature versus time at different heights for air superficial velocity of 2.13 m/s. It has been observed from the Fig. 2 that the bed temperature is higher as we move up in the fluidized bed.

Moisture variation in the solids at the top of the fluidized bed is measured with respect to time and has been presented in the Fig. 3. In the present study, the drying rate is in the falling rate period since the experiments were performed with solids of low initial moisture content. Experiments were repeated for three times and the results were found to be nearly same and the error is very small. Also error bars are indicated in Fig. 3. Fig. 3 for moisture content variation with respect to time is plotted along with the error bars. The same error bars could not be incorporated for temperature vs time of Fig. 2 because the initial temperature of solids varies with room temperature.

From Fig. 2, it is interesting to note that the temperature of the fluidized bed at two different locations decreases initially and as time proceeds it increases. The reason for such variation could be that

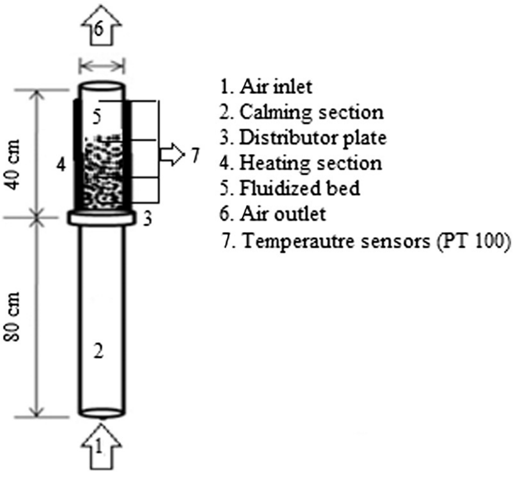

Fig. 1. Schematic diagram of experimental setup.

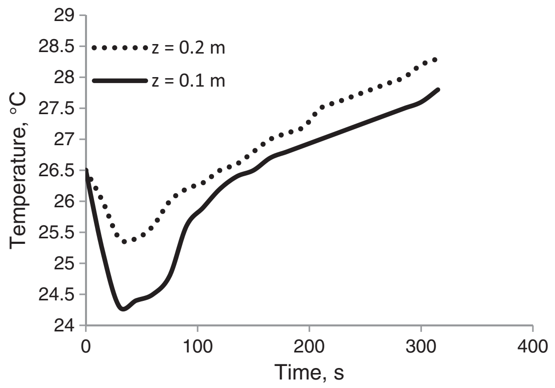

Fig. 2. Experimental data of temperature variation with respect to time at various locations along the fluidized bed.