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Numerical simulation and experimental investigation of plug-flow fluidized bed drying under dynamic conditions

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ABSTRACT

In this study, a mathematical model was presented for prediction of the plug-flow fluidized bed drying process under dynamic conditions resulted from the transient of inlet dry solids mass flow rate. The model previously developed and successfully validated for plug-flow fluidized bed drying process under steady-state condition was the starting point of this study. This model was extended in order to account for the mass and energy transfers between solids and gas phases at dynamic conditions. Additionally, a mass balance equation of dry-based solid holdup and a mass flow rate relationship for outlet solids were developed to predict the transient response of outlet dry solids mass flow rate. The model equations were solved numerically using the finite difference method. To validate the model, drying of rough rice in a laboratory-scale plug-flow fluidized bed dryer was investigated under dynamic conditions. A very satisfactory agreement between simulated and measured results was achieved.

1. Introduction

The goal of any industrial drying process is to produce a product of desired quality at maximum throughput and minimum cost and to maintain these consistently. Good quality implies that the product corresponds to a number of technical, chemical, and biological parameters, each within specified limits. Drying process is one of the most energy-intensive unit operations due to the high latent heat of vaporization and the inherent inefficiency of using hot air as the drying medium. Application of an automatic model-based control system to industrial dryer offers an opportunity to improve the dryer operation and its efficiency. The basic idea of this control system is to use a dynamic model of the drying process that predicts the drying behavior under dynamic conditions caused by the transient of operating parameters (Mujumdar, 2006). A continuous fluidized bed dryer is operated with a continuous stream of solid particles flowing within the bed. The inlet dry solids mass flow rate is an important factor affecting the extent of drying of the outlet product by changing the residence time of solids in the dryer. In continuous dryers, the inlet solids mass flow rate is a common manipulated variable set using the control system (Mujumdar, 2006).

Although a large number of studies in modeling and simulation of continuous fluidized bed dryers have been devoted for steady-state conditions (Nilsson and Wimmerstedt, 1987; Fyhr et al., 1999; Izadifar and Mowla, 2003; Wanjari et al., 2006; Baker et al., 2006; Ramli and Daud, 2007; Bizmark et al., 2010; Apolinar and Martínez, 2012; Khanali et al., 2013), studying the fluidized bed drying process under dynamic conditions rigorously has received little attention. Burgschweiger and Tsotsas (2002) investigated the continuous well-mixed fluidized bed drying process under both steady-state and dynamic conditions. The mixing behavior and residence time distribution of particles in the dryer were considered as a continuous stirred tank reactor. The mass flow rates of solids and gas, air heater capacity, inlet solids moisture content, and inlet gas temperature were varied systematically and a very good agreement between measured and calculated results was obtained. Abdel-Jabbar et al. (2002) presented a model to simulate the dynamic behavior of a continuous well-mixed fluidized bed dryer by combining the drying kinetics for diffusion-controlled system and residence time density function. Only one study on the mathematical modeling of an industrial plug-flow fluidized bed drying process under dynamic conditions has been published by Tacidelli et al. (2012). The proposed model was based on the two-fluid model consists of the gas and particulate phases. The flow of the gas through the bed was considered as a plug and the particulate phase was treated as a perfect mixture. To validate the model, the dynamic responses of the drying process at the dryer outlet to the step changes of +10% and −10% in the inlet solids moisture content were simulated.

The objective of the present work was to study the mathematical modeling and experimental investigation of the plug-flow fluidized bed drying process under dynamic conditions. This

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Nomenclature

a	specific surface area of expanded bed (m^2/m^3)
a_1, a_2, a_3	constant parameter
b_1, b_2, b_3	constant parameter
c_1, c_2, c_3, c_4	constant parameter
C	specific heat (J/kg K)
D	dispersion coefficient (m^2/s)
$\bar{E}$	mean relative error (%)
g	acceleration of gravity (m/s^2)
h	length of the discrete segment along the dryer length (m)
h_{bed}	bed height (m)
h_v	heat of vaporization (J/kg)
h_{weir}	weir height (m)
H	enthalpy (J/kg)
k_1	constant parameter
k_2	constant parameter
L	bed length (m)
M	solids moisture content (dry basis) (kg water/kg dry solid)
n	number of time steps
N	number of discrete segments along the bed length
$\dot{m}_p$	mass flow rate of solids (kg dry solid/s)
P	number of discrete segments along the bed height
q	constant parameter
r	constant parameter
R	drying rate (kg moisture/kg dry solid s)
S	dry-based solid holdup (kg dry solid)
t	time (s)
T	temperature (K or °C)
u	longitudinal solid flow velocity (m/s)
U	gas velocity (m/s)
w	bed width (m)
x	bed length coordinate (m)
X	arbitrary drying attribute
$\bar{X}$	Mean value of arbitrary drying attribute
Y	gas humidity (kg water/kg dry gas)
z	bed height coordinate (m)

Greek letters

α	heat transfer coefficient (W/m^2 K)
ρ	density (kg/m^3)
ξ	solids concentration in the bed (kg dry solid/ m^3 fluidized bed)

Subscripts

0	superficial
bed	bed
exp	experimental
g	gas
in	input
out	output
p	particle
pre	predicted
ref	reference
v	water vapor
w	water

modeling was an extension of the steady-state plug-flow fluidized bed drying model developed by Khanali et al. (2013). In this way, a mathematical model was developed to predict the solids moisture content and temperature and outlet gas humidity and temperature along the dryer length as well as the outlet solids moisture content and temperature under dynamic conditions resulted from the transients of inlet solids mass flow rate. The accuracy of the model was also investigated by comparison with the experimental data of plug-flow fluidized bed drying process under dynamic conditions.

2. Development of the model

The study of drying process under dynamic conditions can be conducted by considering the start-up behavior or the step-responses resulted from the transient of various operating parameters. Here, it is refrained from discussing different types of start-up behavior and is concentrated only on the transients initiated by step change in inlet solids mass flow rate.

The schematic differential model of the proposed plug-flow fluidized bed drying process at dynamic condition is presented in Fig. 1. The bed of the dryer is divided horizontally into major control volumes of dx length ($h_{bed}wdx$) as Fig. 1a and each of these control volumes is divided vertically into minor control volumes of dz height ($wdxdz$) as Fig. 1b. This differential scheme of the dryer model at dynamic condition is similar to the scheme given by Khanali et al. (2013) for the dryer model under steady-state condition except for the accumulation terms that shows the change of moisture or energy in the major and minor control volumes with respect to time. On the other hand, if the accumulation terms in the dynamic model are set to zero, it becomes a steady-state model. Important assumptions and features of this model are as follow:

- Dispersed plug-flow of solids within the bed from inlet to outlet of the dryer, i.e. the combination of ideal plug-flow at constant longitudinal solid flow velocity (bulk flow) and longitudinal dispersion.
- Ideal plug-flow of the gas from bottom to top of the bed.
- Perfect mixing of particles in vertical direction, which results the uniform moisture content and temperature in the major control volume.
- Consideration of uniform physical and fluidization properties of the particles along the dryer length.

In the case of the first above assumptions, a dimensionless group (D/uL), known as the dispersion number can be used to characterize the dispersion phenomenon or the deviation from ideal plug-flow. When the dispersion number is zero, the flow is ideal plug-flow; for values of dispersion number less than or equal to 0.01, the particles flow can be considered approximately as plug-flow with small dispersion, and the values of dispersion number more than 0.01 show a large deviation from ideal plug-flow (Khanali et al., 2013).

In order not to disturb the main text, a complete definition about the model parameters such as bed porosity, solids concentration in the bed, specific surface area of expanded bed, dispersion coefficient, heat transfer coefficient, and thermodynamic equations of air-vapor system can be found in the previous work by Khanali et al. (2013).

The balance equations corresponding to the scheme of Fig. 1 and expressing the model are given in the following subsections.

2.1. Mass balance on moisture in the particles

The mass balance on moisture in the particles over the major control volume under dynamic conditions considering the input