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CFD analysis of fluidized beds using wastes from post-consumer carton packaging

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ABSTRACT

Fluidized bed reactors can be used for fast pyrolysis of polyethylene-aluminum composite (LDPE/Al) to achieve good gas-solid mixing together with high rates of heat and mass transfer in bed columns. Pyrolysis of waste from post-consumer carton package (i.e., polyethylene-aluminum composite) reduces the manufacturing costs of new packages as it permits to produce them using the recovered aluminum and polyethylene in the process. Therefore, this research aims at modelling and analyzing the gas-solid flow in fluidized beds composed of sand and LDPE/Al mixtures. For all mixtures used, results show that gas-solid flow can be well described by the Eulerian-Eulerian Granular model coupled with the usage of parameterized Syamlal-O'Brien's model for momentum transfer between phases. For bed mixtures with up to 20% LDPE/Al composite, the bed pressure drop can be predicted by the model with an error of less than 18%. In addition, for bed mixtures operating at air velocities higher than 50% minimum fluidization, significant segregation of LDPE/Al was not observed. This result indicates that bed mixtures can achieve a good gas-solid contact in the bubble fluidization regime and can be used as a fluidized bed reactor for pyrolysis of wastes from post-consumer carton packages.

1. Introduction

Carton packages are widely used to contain and preserve food products. Because of laminar structure (i.e., composed of 75% paper, 5% aluminum and 20% polyethylene on average), such packages prevent the contact of the food with the microorganisms, oxygen, and light. This characteristic permits the food to be stored for a long period of time not requiring refrigeration. On the other hand, due to the increased market demand, large amount of carton packaging waste in the municipal solid waste can be generated. Therefore, as reported by Wu and Chang [1] and Korkmaz et al. [2], the conversion of carton packaging waste to valuable materials is important from economic and environmental viewpoint.

Pyrolysis is the only technology that allows aluminum recovery from Tetra Pak® packages and has been studied by many researchers [1–5]. In large-scale production, the fluidized bed reactor becomes a promising gas-solid contactor for pyrolysis of polyethylene-aluminum composite (i.e., LDPE/Al composite, sub product of post-consumer recycling processes from paper industry). However, because of complex flow behavior and phase interactions the modelling of fluidized bed reactors has been a great challenge.

Computational fluid dynamics (CFD) is a promising tool to support the investigation of the complex phenomena occurring between the gas and particle phases in fluidized and spouted beds as demonstrated by several research groups [6–15]. For many years, contributions to the analysis of multiphase flows in fluidized beds could be done based on the research of Kinetic Theory of Dense Gases summarized by Chapman and Cowling [16]. In the late of 80 s and 90 s, Ding and Gidaspow [17], Gidaspow [18], Jenkins and Savage [19], Lun et al. [20] and Van Wachem [21] applied the fundamentals of the Kinetic Theory for modelling flow regimes achieved in fluidized beds of monosized-particles. For particles with different sizes, the multiphase flow model using the Kinetic Theory of dense gases was recently reviewed by Gidaspow and Jiradilok [22] and by Hrenya [23]. The multiphase model describing fluidized beds with particles of different size was analyzed and extended by Jenkins and Mancini [24], Iddir and Arastoopour [25], Hulin et al. [26] and Iddir et al. [27].

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Nomenclature

C_D Drag coefficient
d_{si} Solid phase i particle diameter
e_{ss} Restitution coefficient between solids
$g_{0,ss}$ Radial distribution function for one solid phase
$g_{0,s1s2}$ Radial distribution function for two solid phases
$\vec{g}$ Gravity acceleration
$\bar{\bar{I}}$ Unit tensor
K_{gsi} Interface momentum exchange coefficient
k_{Θ_s} Granular temperture difusion coeficient
m Mass
P Pressure
ΔP Bed pressure drop
Re Reynolds number $\equiv \frac{\rho v d}{\mu}$
Δt Time step
u Superficial velocity
$\vec{v}$ Velocity
$v_{r,s}$ Terminal velocity for solid phase

Greek symbols
α Volumetric fraction
γ_{Θ_s} Granular energy dissipation by heat due to the inelastic solid-solid collisions per unit volume
ε Porosity
Θ Granular temperature
λ Bulk viscosity
μ Shear viscosity
$\bar{\bar{\tau}}$ Shear tensor
ρ Density
Φ Sphericity
ϕ_{gs} Granular energy exchange between gas and solid phases per unit volume

Abbreviations
AL Aluminum
CFD Computational fluid dynamic
LDPE Low density polyethylene

Subscribed
g Fluid phase, gas
si i^{th} Granular phase, solid
mf Minimum fluidization
r Reference

For modeling fluidized beds, there are two different approaches: the Eulerian-Lagrangian and Eulerian-Eulerian model. The Eulerian-Lagrangian model solves the Newton's equations of motion for each individual particle including the effects of particles collisions and forces acting on the particle. The Eulerian-Eulerian model considers the gas and solid as two continua and non-interpenetrating phases. This model solves the continuity, momentum and energy equations for each phase involved. As in the fluidization regime, solid particles present high concentration in the column, the Eulerian-Eulerian model becomes more suitable as compared to the Eulerian-Lagrangian model.

In spite of CFD has been contributing to the simulation of multiphase flow reactors along the years [28–36], for designing fluidized bed reactors with either two size particles or particles with different densities, the usage of experimental unit to obtain fluid dynamic data is still needed. Experimental units not only allow practitioners to change reactor design, but also improve their model assumptions to better describe the flow characteristics achieved in such multiphase contactors.

For application of fluidized beds as pyrolysis reactors of post-consumer carton wastes, this research aims at modelling and analyzing the gas-solid flow in fluidized beds composed of sand and LDPE/Al mixtures. For this purpose, experimental tests are carried out to obtain fluid dynamic data and CFD simulations are used for predicting the air-LDPE/Al-sand flow achieved in a fluidized bed unit.

2. Eulerian-Eulerian model for describing fluidized beds

For modelling fluidized beds the concepts of conservation laws are used as mathematically represented by Continuity, Momentum and Granular Kinetic Energy equations (see Table 1). In order to close the set of equations shown in Table 1, constitutive relations are needed. These constitutive relations, presented in Table 2, are obtained by either the usage of empirical correlations or the application of the Granular Kinetic Theory.

For granular flows the momentum exchange between the phases is estimated using fluid-solid and solid-solid exchange coefficients, which are empirically determined. For dilute and dense fluidized bed regimes, the Syamlal's [37] correlation, based on measurements of particles terminal velocities, is suitable to describe momentum transfer between phases as verified by Zimmermann and Taghipour [38] and by Behjat et al. [39] research group.

Syamlal-O'Brien [40] has changed the previous correlation by using experimental data of minimum fluidization velocity and porosity. In sequence, for gas-solid flow composed of two granular phases, Syamlal [41] has proposed a coefficient for drag model considering the interactions between the granular phases (Eq. (8)). This model is used for simulating the gas-solid flow in a fluidized bed process composed of LDPE/Al and sand mixtures.

For describing the fluidized bed comprising mixtures of LDPE/Al composite and sand schematically showed in Fig. 1, the following assumptions are needed. Initial conditions: a) the particles in the bed present a defined bed height and solid volume fraction (ε_s) according to the experimental data for each either mono-sized particle or particle mixture; b) the bed is static i.e., particle velocity is zero; c) the air in the bed shows the volume fraction related to prescribed solid volume fraction (1-ε_s); the air velocity in the bed is zero. Boundary conditions: a) at the bed inlet, the air flux is in the axial direction (y-axis) and is defined for each operating condition; whereas, the particle velocity is zero; b) at the bed outlet, the pressure is defined to be atmospheric; c) at the column wall, for primary phase (air), a no slip condition is defined; whereas, for secondary phase (solid) a free slip condition is chosen.

3. Experimental methodology

3.1. Experimental process unit

To obtain the fluid dynamics data a bench-scale fluidized bed process unit was used, as schematically shown in Fig. 2. The apparatus consists of a transparent glass column and other peripheral equipment such as: a centrifugal blower (by IBRAM with 2 CV power and 4.5 m^3/min) for injecting air into the bed, pressure transducers to measure the bed pressure drop (Dwyer 616C-4, from 0 to 4981 Pa operating range and 1% accuracy) located at 5 cm bed inlet, a thermo-anemometer to obtain the superficial air velocity and thermocouples to measure the air temperature at the bed inlet. A supervisory system was developed in LabVIEW program language. This permits to obtain data of bed sensors using A/D data acquisition board by National instruments connected to computer (Core i3, 3.30 GHz, 4 GB RAM).