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Original Research Paper

Fluidization of cylinder particles in a fluidized bed

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ABSTRACT

An experimental study of the flow regimes and transitions in a fluidized bed (cross-section of 200 mm × 200 mm and height of 2000 mm) containing a mixture of cylindrical particles and silica sand is carried out. Six different flow regimes are identified: fixed bed (F), bubbling fluidization (B), transition fluidization (T), partial fluidization (P), complete fluidization (C) and unable to fluidize (N). The flow regime characteristics are described using schematic diagrams and photographic images. Based on the flow regime classification, three types of flow regime transition routes are explained. The effect of various operating parameters on the flow regime transition is determined and the resulting flow regime map is presented. Two unstable fluidization patterns are observed and their fluidization mechanisms are discussed. It is shown that the change of the ΔP-u_f profile, where ΔP is the bed pressure drop and u_f is the superficial gas velocity, indicates when a flow regime transition occurs and the reproducibility of the ΔP-u_f curve identifies fluidization stability. Furthermore, a contact force model for a cylindrical particle in a bed material cloud is developed considering particle orientation, based on which a theoretic model for cylindrical particle fluidization termination velocity (u_b) was derived and validated.

1. Introduction

With the development of economic and rapid urbanization, China now encounters not only the problem of municipal solid waste (MSW) disposal but also the impending demand for alternative energy and a clean environment [1,2]. That is why MSW incineration is playing an increasingly important role in MSW disposal because it offers an integrated solution for these problems [3]: it can effectively reduce the volume of MSW while simultaneously producing electricity and/or steam for heating. With the help of adequate flue gas treatment, it is also a safe and environmentally-friendly method compared to other methods like landfilling. As one of the most promising technologies for MSW incineration disposal, fluidized bed combustion has gained great attention because of its advantages, such as high efficient heat and mass transfer, homogeneous temperature distribution, and sufficient gas-solid contacting. Also, fluidized beds can easily adapt to low-grade fuels when co-firing with coal, which makes it very suitable for China where low caloric value MSW [4] and coal are abundant.

Waste particles are usually large in size and diverse in shape, which makes them difficult to fluidize. To aid in fluidization, inert bed material like sand is typically added. Hence, MSW fluidized bed combustion is a complex mixture involving at least two kinds of particles with different sizes, shapes, and densities; this gives rise to some unpredictable negative phenomena (e.g., segregation, local defluidization, etc.) leading to totally different flow regimes from conventional fluidized beds. As a result, the temperature profile and chemical reactions in MSW fluidized beds will tend to be nonhomogeneous, jeopardizing its reliable and efficient operation. A solution to this problem requires an optimized design and operation for MSW fluidized beds. However, although efforts in the research of multi-component mixture fluidization have been made for many years, our understanding of this process still remains incomplete. This is especially true for mixtures consisting of large non-spherical particles in a typical bed material (i.e., silica sand), which makes the design and operation of MSW fluidized beds still based on intuition and rules of thumb.

In previous literature focused on mixtures of diverse material, researchers mainly focused on the minimum fluidization velocity [5–13], effect of operating parameters [7,14] and mixing/segregation behavior [15–21]. Moreover, most of these studies

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Nomenclature

a	identifier of complete fluidization (C) transition point
Asr	cylindrical particle aspect ratio, i.e. l/d_i
b	identifier of cylindrical/spherical particle fluidization termination velocity
c	identifier of fixed bed (F) transition point
d_i	diameter of cylinder particle (mm)
d_j	average diameter of bed material particle (mm)
d_m	modified particle diameter (mm)
d_v	volume equivalent diameter of cylinder particle, diameter of Sphere A (mm)
D	fluidized bed width (mm)
e_{ij}	coefficient of restitution
$F(\beta)$	probability density function (PDF) of cylindrical particle orientation
g	gravitational acceleration (m/s^2)
H	average height that the bed material reaches (m)
H_0	static bed height (mm)
i	identifier of cylindrical particle
j	identifier of bed material
k	identifier of pressure sample points
K	derived parameter defined in Eq. (17)
l	length of cylindrical particle (mm)
m_i	mass of a cylindrical particle (kg)
m_j	mass of a bed material particle (kg)
N	total number of pressure sample points
N_{jbase}	total number of bed material particles colliding on cylindrical particle base face
$N_{jelement}$	total number of bed material particles colliding on cylindrical particle lateral face
p_k	pressure of the kth sample point (kPa)
$\bar{p}$	average pressure value of sample points sequence (kPa)
P_{ij}	collision force (N)
$P_{ij}(\beta)$	collision force function (N)
P_{ijbase}	collision force on particle i on the base face (N)
$P_{ijlateral}$	collision force on particle i on the lateral face (N)
P_{ijmax}	maximum collision force (N)
P_{ijmin}	minimum collision force (N)
r	Pearson correlation coefficient
$\overline{R}^2$	adjusted coefficient of determination
R_i	radius of cylindrical particle (m)
R_j	average radius of bed material particle (m)
S_{base}	collision area of cylindrical particle base face (m^2)
$S_{element}$	collision area of cylindrical particle lateral face element (m^2)
SD	pressure fluctuation standard deviation (kPa)
u_f	superficial gas velocity (m/s)
u_a	complete fluidization (C) transition velocity (m/s)
u_b	cylinder/large spherical particle fluidization termination velocity (m/s)
u_c	fixed bed (F) transition velocity (m/s)
$u_{f\max}$	upper limit of gas velocity in this study (m/s)
u_i	final velocity of the cylindrical particle i velocity after collision (m/s)
u_j	final velocity of the bed material particle j velocity after collision (m/s)
u_{mf}	minimum fluidization velocity (m/s)
v_i	velocity of the cylindrical particle i velocity before collision (m/s)
v_j	velocity of the bed material particle j velocity before collision (m/s)
V_j	volume of single bed material particle j (m^3)
V_{totalj}	total volume of bed material particles j (m^3)
V_{totali}	total volume of cylindrical particles i (m^3)

Greek symbols

α	cylinder/large spherical particle mass fraction
β	angle between cylindrical particle axis and horizontal line (radius)
$\bar{\beta}$	derived parameter from mean value theorem in Eq. (13)
γ	angle between the particle motion streamline and the line connecting the face element and particle i axis (radius)
δ	momentum transfer coefficient
δ_{base}	momentum transfer coefficient for a base face collision
$\delta_{element}$	momentum transfer coefficient for a lateral face collision
ΔL	the distance covered by bed material in Δt seconds
ΔM_i	one-dimensional momentum increase of a single cylindrical particle i from single collision ((kg m)/s)
ΔM_{ibase}	momentum increase from base face collisions ((kg m)/s)
$\Delta M_{ielement}$	momentum increase from lateral face element collisions ((kg m)/s)
$\Delta M_{ilateral}$	momentum increase from lateral face collisions ((kg m)/s)
ΔP	bed pressure drop (kPa)
Δr	width of face element $S_{element}$ on lateral face (m)
Δt	temporal parameter for collision model derivation (s)
ε_0	cylindrical particle static packing voidage
ε	collision force modification coefficient
ρ_i	cylindrical particle density (kg/m^3)
ρ_j	bed material particle density (kg/m^3)
Φ	cylindrical particle sphericity
φ_j	volume fraction of bed material

neglected the influence of particle shape because differences in both particle size and shape were relatively small. Research on mixtures consisting of large non-spherical particles and inert bed material is limited [13,19,22–24] especially in terms of behavior modeling [25,26] and flow regime [19,23,27]. Furthermore, the mass fraction of non-spherical particles in existing studies is relatively low (usually lower than 30%). The effect of high mass fractions of non-spherical particles is seldom reported.

As a favorable flow regime is a vital necessity for reliable waste fluidized bed combustion, the current study focuses on the flow regime classification and transition mechanism for binary mixtures of large non-spherical particles and inert bed material. Specifically, cylindrical particles are used to mimic MSW particles and silica sand is used as the inert bed material. Typical flow regimes are classified according to pressure drop curves and visual observations. Effects of operating conditions (e.g., superficial gas velocity (u_f), static bed height (H_0), particle sphericity (Φ), and particle mass fraction (α)) on flow regime transition are studied. Furthermore, a contact force model for a cylindrical particle in a bed material cloud is derived and results, based on various operating conditions, are presented.

2. Experimental procedures

2.1. Experimental setup

Fig. 1 schematically shows the experimental setup which contains a square fluidized bed, an air supply system, and a pressure measurement system. The fluidized bed is a transparent square column made of Plexiglas with cross section of 200 mm × 200 mm and height of 2000 mm. Nine pressure taps are located on one

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