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Fluidization characteristics of a bubbling gas–solid fluidized bed at high temperature in the presence of interparticle forces

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HIGHLIGHTS

- The hydrodynamics of a bubbling gas–solid fluidized bed was studied at high temperature.
- The investigation was attempted in the virtual absence and presence of interparticle forces.
- The level of interparticle forces was adjusted through the formation of eutectics on the surface of particles.
- Smaller bubbles passed through a bed of coarse particles at elevated temperatures.
- The presence of interparticle forces led to a multiplicity of behaviors.

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ABSTRACT

The fluidization behavior of bubbling fluidized beds of coarse particles was investigated between 700 and 1000 °C for superficial gas velocities ranging from 0.6 to 1.5 m/s. The objective of the study was to highlight modifications in the bed behavior with the operating temperature at conditions under which the role of hydrodynamic forces (HDFs) or interparticle forces (IPFs) was dominant. To this end, the experimental work was divided into two phases. In the first phase, the influence of temperature on the hydrodynamics of a bubbling fluidized bed of coarse particles for which HDFs were dominant was investigated. In the second phase, the surface characteristics of the fluidized particles were primarily modified through the formation of eutectics resulting from a chemical reaction between the bed material and alkali/alkali earth metal based reagents that were introduced into the bed throughout the periods of solid fuel combustion at elevated temperatures. This then triggered changes in their fluidization characteristics with increasing temperature while IPFs were present in the bed. Experimental results revealed that the flow dynamics of a bubbling bed of coarse particles at high temperature was principally influenced by the variation of the gas density with temperature when IPFs did not play a discernible role. Nevertheless, with the presence of different levels of IPFs in the bed, a multiplicity of behaviors was realized at elevated thermal levels. Consequently, the physical and/or physico-chemical changes in the fluidized particles due to an increase in temperature and the variation in the physical properties of the fluidizing gas should be seriously considered when attempting to successfully design and operate gas–solid fluidized beds at high temperature.

1. Introduction

Gas–solid fluidized beds have been commonly employed in chemical industries in such areas as fluidized catalytic cracking, catalytic oxidation, combustion and gasification of different solid fuels, and polymerization [1,2], often operating at high temperature with respect to the particles being fluidized in the bed. Since they offer critical advantages, such as the ability to provide high heat and mass transfer rates, high combustion efficiency, low emission levels, and good fuel flexibility to process a broad variety of solid fuels (biomass, various waste materials, low grade coal) or blends (co-firing with conventional fuels) [3–5], they will find many additional industrial applications in the near future that will coincide with the rarefaction of conventional resources. Therefore, a comprehensive understanding of the fluidization characteristics of a fluidized bed at high temperature is of prime importance to establish successful design criteria for this technology.

Research on the effect of temperature on the hydrodynamic aspects of gas–solid fluidized beds was started in the mid-1970s.

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Nomenclature

Acronyms

HDFs	hydrodynamic forces
IPFs	interparticle forces
MSW	municipal solid waste
PSD	power spectral density
XPS	X-ray photoelectron spectroscopy

Symbols

A_i	area of the peak for a given element in the resulted XPS measurement (eV count/s)
d_c	column diameter (m)
d_p	mean particle size (μm)
h_0	static bed height (m)
n	power of absolute temperature; $\mu_g \propto T^n$, $0.6 < n < 1.0$ (–)
Re_p	particle Reynolds number (–)
$RA\%$	relative atomic percentage (–)
SF_i	sensitivity factor for an element in XPS measurement (–)
T	absolute temperature (K)
T_m	melting temperature (°C)
U_c	transition velocity from bubbling to turbulent fluidization regime (m/s)
U_g	superficial gas velocity (m/s)
U_i	interstitial gas velocity (m/s)
U_{mf}	minimum fluidization velocity (m/s)
U_{mb}	minimum bubbling velocity (m/s)

Greek letters

ε_0	settled bed voidage (–)
ε_{mb}	minimum bubbling voidage (–)
ε_{mf}	minimum fluidization voidage (–)
μ_g	gas viscosity (Pa.s)
ρ_g	gas density (kg/m^3)
$\rho_g U_g^2$	gas momentum flux (Pa)
ρ_p	particle density (kg/m^3)

Findings, however, are still controversial to provide a satisfactory understanding of the phenomena that is responsible for changes in the fluidization behavior between ambient and high temperatures [2,6]. The major source of this controversy is ascribed to the lack of insight into the relative importance between hydrodynamic forces (HDFs) and interparticle forces (IPFs) [7,8]. Although some researchers attempted to approach this difference on the sole basis of variation in HDFs [9–13], it has been proven that most of the conventional models/equations, which were based purely on hydrodynamic principals, became increasingly inaccurate when the temperature increased [14–16]. It is believed to be the direct consequence of ignoring the modification in the solid phase, i.e., the level of IPFs, at thermal levels well above ambient temperature. Some peculiar observations were reported for the bed behavior at high temperature, which could not be solely explained in light of changes in the fluidizing gas properties. They include an increase in the settled bed voidage ε_0 in the complete absence of gas flow [3,17–20], an increase in the minimum fluidization and bubbling voidages (ε_{mf} and ε_{mp}, respectively) [3,17,18,20–22], the presence of an overshoot at the minimum fluidization velocity U_{mf} in the bed pressure drop profile for powders showing typical Geldart group B [23] behavior at ambient conditions [24,25], or the presence of a more profound overshoot at U_{mf} for powders exhibiting typical Geldart group A characteristics at room temperature [7,8] as well as the concave trend for the variations of U_{mf} and the interstitial gas velocity U_i with the system temperature for fine particles [3,7,18,21,25]. Thus, it turned out to be obvious that the combined effects of HDFs and IPFs govern the bed hydrodynamics though their relative importance and the way in which IPFs, in particular, influence the bed behavior is not clear.

Increasing the system temperature decreases the gas density ρ_g (ρ_g being inversely proportional to the absolute temperature T) and increases the gas viscosity μ_g (μ_g being proportional to T^n, where n is usually between 0.6 and 1.0) [26,27]. These changes can in turn modify the magnitude of fluid forces exerted on the particles. Van der Waals and electrostatic forces are the main types of IPFs in a dry environment [28,29]. The magnitude of the van der Waals forces acting between particles in mutual contact enhances with an increase in the bed temperature as the molecular dipole pulsation around the contact point is enhanced by thermal excitation [30]. Also, the viscous flattening of solid particles occurring before sintering [31] gives place to a larger interparticle contact area, promoting the effectiveness of the van der Waals forces. The electrostatic forces, which are only important for particles larger than 50 microns in diameter [32], become less influential at higher thermal levels [16,33,34] due to an increase in the electrical conductivity of particles as the temperature increases [35,36]. The presence of a material bridge between the particles at high temperature can arise either from the formation/addition of a liquid or the structural/chemical changes at the particle surface, e.g., through sintering, crystallization or plastic deformation [37]. The cohesive force resulting from the material bridge, either liquid or solid, is much larger in magnitude than the van der Waals and electrostatic forces [29,32,37,38]. Sintering originates from the migration of holes/lattice cavities or the movement of atoms to a less dense area of the material on the surface of particles [39] and yields a solid–solid bond between the particles in contact at its final stage. The formation of a trace amount of liquid in high temperature fluidized beds is principally due to the presence of impurities with a low sintering temperature within the bed. The impurities sinter/melt at the operating temperature and can further react with each other or other solids producing new compounds [40] with a low melting temperature (eutectic), which liquefy under the above operating conditions. For instance, in the case of the combustion and gasification of biomass, wastes, and low rank coals the ash sintering and chemical reaction between the alkali/alkali earth metal elements in the solid fuels/ash and the bed material, commonly silica sand, are known as the major sources of particle stickiness in the bed [5,41–44]. If one of the IPFs is in the same order of magnitude as the weight of the particle, the particles are called sticky and the fluidization behavior can be modified [5]. Therefore, it seems clear that the fluidization characteristics of a gas–solid fluidized bed at elevated temperatures are significantly more complicated than what was initially thought.

Reviewing extensive studies on the influence of temperature on gas–solid fluidization behavior reveals that they can be categorized into five groups: (i) literature studies that were devoted to low gas velocities, either for the fixed bed state or near the minimum fluidization/bubbling velocity [3,7–13,17–22,24,25,45–61], which do not generate considerable industrial interest; (ii) studies to model the limiting state of defluidization when fluidizing pure material at high temperature [62–65]; (iii) investigations on the influence of bed temperature on the transition velocity from bubbling to turbulent fluidization regime U_c [66–69]; (iv) research that focused on the variation of the entrainment rate with an increase in temperature [16,70–74]; and (v) detailed studies that concentrated on bub-