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Review

Effects of temperature, pressure, and interparticle forces on the hydrodynamics of a gas-solid fluidized bed

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HIGHLIGHTS

- Effects of temperature and pressure on fluidization behavior are reviewed.
- Gas-solid systems with and without interparticle forces are considered.
- Variations in both hydrodynamic and interparticle forces must be considered for a reliable prediction of bed behavior.
- Hydrodynamic study at high temperature and pressure simultaneously is required.

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ABSTRACT

An in-depth examination of the hydrodynamics of gas-solid fluidized beds at high temperature and pressure is critical for their design and operation owing to the global trend of processing lower quality feedstocks, e.g., high ash content coal, biomass, and waste, in these units. Current knowledge on gas-solid fluidization, though, refers to ambient conditions and the hydrodynamic models based on these conditions by merely changing the gas properties, i.e., its density and viscosity, are generally employed to estimate the overall performance of gas-solid fluidized bed processes under extreme conditions. This strategy, however, overlooks possible modifications induced by the operating conditions on the structure and dynamics of fluidized particles, i.e., the level of interparticle forces. With the development of new processes adopting gas-solid fluidized beds under extreme conditions, a comprehensive review of the experimental and simulation studies of gas-solid fluidization at elevated temperatures and pressures and in the presence of interparticle forces is warranted. This review addresses the effects of temperature, pressure, and interparticle forces on the fluidization characteristics of gas-solid fluidized beds for a wide spectrum of particle systems, ranging from Geldart groups A, B, and D classifications, refer to the fluidization behavior at ambient conditions.

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Nomenclature

Acronyms

HDFs	hydrodynamic forces
IPFs	interparticle forces
TDH	transport disengagement height

Symbols

d_p	mean particle size (μm)
n	power of absolute temperature; $\mu_g \propto T^n$, $0.6 < n < 1.0$ (–)
Re_p	particle Reynolds number (–)
T	absolute temperature (K)
U_c	transition velocity from bubbling to turbulent fluidization regime (m/s)
U_b	bubble rise velocity (m/s)
U_g	superficial gas velocity (m/s)
U_{mf}	minimum fluidization velocity (m/s)
U_{mb}	minimum bubbling velocity (m/s)
U_t	terminal velocity (m/s)
$U_g - U_{mf}$	excess gas 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)
ρ_p	particle density (kg/m^3)

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1. Introduction

When one contemplates a range of industrial processes, including FCC regeneration, coal combustion and gasification, gas phase olefin polymerization, and iron ore or mineral sand reduction, a very broad range of parameters is encountered: gas molecular weight 2–600 kg/kmol, particle size 10–5000 μm, particle density 550–4800 kg/m^3, temperature to 1700 °C, and pressure to 30 bar [1–7]. It is also well recognized in some industrial sectors (e.g., mining and petroleum industries) that feedstocks are rapidly changing due to the shortage of conventional resources. New fuel sources and blends of feedstocks, such as biomass, coal, waste, and petcoke, are typical for many current and future industrial applications. Gas-solid fluidized beds operating under extreme conditions are considered as original solutions and technologies that have the potential to process complex raw materials, including non-renewable and renewable resources, to support the increasing needs of society. The hydrodynamics of a gas-solid fluidized bed affects heat and mass transfer rates in the bed and can in turn influence the overall reaction rate in gas-solid fluidized bed reactors. Variations in operating conditions, i.e., temperature and/or pressure, can change the gas properties and the level of interparticle forces (IPFs) in a gas-solid fluidized bed. Accordingly, in order to provide a comprehensive understanding of the bed hydrodynamics under different operating conditions, variations in both hydrodynamic forces (HDFs) and IPFs must be taken into account.

Increasing the bed temperature causes the gas viscosity μ_g to increase (μ_g being proportional to T^n, where n is usually between 0.6 and 1.0) and the gas density ρ_g to decrease (ρ_g being inversely proportional to the absolute temperature T) [8,9]. These modifications can change the magnitude of fluid forces exerted on the particles. Electrostatic and van der Waals forces mainly determine the magnitude of IPFs in a dry environment [10,11]. When the bed temperature increases, the magnitude of the electrostatic forces decreases [12–14] due to an increase in the electrical conductivity of the particles [15,16]. Since the molecular dipole pulsation around the contact point between particles in mutual contact is enhanced by thermal excitation, the magnitude of the van der Waals forces increases with the bed temperature [17]. The viscous flattening of solid particles occurring before sintering [18] results in a larger interparticle contact area and, hence, increases the magnitude of the van der Waals forces. The formation/addition of a liquid or the structural/chemical changes at the particle surface, e.g., through sintering, crystallization or plastic deformation, can give rise to the presence of a material bridge between the particles at elevated temperatures [19]. The electrostatic and van der Waals forces are insignificant compared to the cohesive force resulting from the material bridge, either liquid or solid [11,19–21]. Materials migrate to the contact area during sintering due to diffusion, viscous flow or some other mechanisms or combination of mechanisms [21,22], thus yielding a solid-solid bond between the particles in contact at the final stage. The formation of compounds with a low melting temperature, i.e., eutectics, principally causes a trace amount of liquid to form in high temperature fluidized beds. The presence of elements/compounds with a low sintering temperature within the bed, which sinter/melt under the high temperature operating conditions and further react with each other or other solids, leads to the formation of eutectics [23]. For example, the ash sintering and chemical reaction between the alkali/alkali earth metal elements in the solid fuels/ash and the bed material, usually silica sand, are known as the main causes of the particle stickiness in the bed when combusting and/or gasifying low rank coals, biomass, and waste [24–31]. The bed hydrodynamics can be altered if one of the IPFs is in the same order of magnitude as the weight of the particle [25].

Unlike temperature, changing the system pressure essentially has a single effect on the gas density because the gas viscosity is a very weak function of pressure [32]. Increasing the bed pressure can also enhance the gas adsorption on the surface of particles and, thus, the magnitude of IPFs where they can also modify the fluidization behavior of a gas-solid fluidized bed [33–35]. When the magnitude of IPFs is very low and/or does not change with the operating conditions, the variation in the gas properties defines the change in the fluidization characteristics for a given powder. The particle size information, in this case, helps to find that the modification in the bed hydrodynamics is governed either by the