

EFFECTS OF TEMPERATURE, PRESSURE, AND INTERPARTICLE FORCES ON GAS-SOLID FLUIDIZATION BEHAVIOR

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Abstract – Gas-solid fluidized beds are widely employed in the chemical industry and their applications continue to increase, especially under extreme conditions. Bed hydrodynamics influences the heat and mass transfer rates and, in turn, the overall reaction rate of a gas-solid fluidized bed reactor. Thus, particular attention to the hydrodynamics of gas-solid fluidized beds at elevated temperatures and pressures is critical for their design and operation. Operating a gas-solid fluidized bed at thermal and pressure levels well above the ambient conditions can change the level of interparticle forces in parallel with hydrodynamic forces. The bed flow dynamics can be modified by these variations. Although the role of interparticle forces in changing the bed behavior under extreme conditions is often disregarded, it can result in drastic changes in the fluidization behavior under certain circumstances. The objective of this article is to briefly review the effects of temperature, pressure, and interparticle forces on the hydrodynamics of gas-solid fluidized beds for a wide spectrum of particles that behave like Geldart groups A, B, and D at ambient conditions.

INTRODUCTION

Gas-solid fluidized beds are widely applied in the chemical industry due to their unique advantages, including excellent gas-solid contact, favorable heat and mass transfer characteristics, uniform and controllable temperature, and the ability to handle a wide variety of particulate properties and to process fuel in any physical form (Kunii and Levenspiel, 1991, Yates and Lettieri, 2016). With rising concerns about secure materials and energy resources, feedstocks are changing in several chemical industrial sectors, e.g., in energy and synthesis fuel production sectors as well as mining and petroleum industries, owing to the shortage of conventional resources. For instance, new fuel sources or blends of feedstocks, such as biomass, various waste materials, low grade coal, and petroleum coke, which are lower in quality compared to conventional fossil fuels, are typical for many current and future industrial applications. Also, given the increasing emphasis on the development of green processes, in order to limit the criteria air contaminants, e.g., SO_x, NO_x, HCl, Hg, and meet stringent environmental constraints, sorbents have been added with the fuel into the fluidized bed reactors to trap the contaminants either in the bed or after it. The presence of inorganic alkali components, e.g., potassium and sodium, either in the lower quality fuel or sorbent additives, could make the bed hydrodynamics significantly more complex due to the formation of eutectics and agglomerates of particles as the level of interparticle forces (IPFs) can dramatically increase.

Since high temperature and pressure gas-solid fluidized beds are known as the most proper chemical reactors to process the new feedstocks while meeting the stringent environmental constraints, their appropriate design and operation require that particular attention be given to the bed hydrodynamics under extreme operating conditions. The influences of operating temperature and pressure on the fluidization behavior are generally estimated by simply accounting for the variations in the gas properties, i.e., its density and viscosity, in the hydrodynamic models that are based purely on hydrodynamic principals and developed with fluid dynamic data collected at near-ambient conditions. This strategy, however, overlooks possible modifications induced by the operating conditions on the structure of fluidized particles, i.e., the level of IPFs, and, hence, on their dynamics, which subsequently makes the accuracy of the prediction dubious (Yates and Lettieri, 2016). With the development of new technologies employing gas-solid fluidized beds under extreme conditions, a review of in-depth research efforts on gas-solid fluidization at elevated temperatures and pressures and in the presence of IPFs is warranted. The objective of this work is to briefly address the influences of temperature, pressure, and IPFs on the gas-solid fluidization behavior of a wide spectrum of particle systems, including Geldart groups A, B, and D classifications at ambient conditions.

EFFECTS OF TEMPERATURE AND PRESSURE ON THE VARIATIONS OF HYDRODYNAMIC AND INTERPARTICLE FORCES

Magnitudes of hydrodynamic and interparticle forces can be altered upon changing the operating conditions in a gas-solid fluidized bed of a given powder. While the change in the level of hydrodynamic forces (HDFs)

results from the variations in the gas properties, the modification in the surface properties of particles yields the change in the level of IPFs. Consequently, the contributions of IPFs and HDFs must be taken into consideration concurrently to provide a comprehensive understanding of the bed behavior at elevated temperatures and pressures.

When the bed temperature increases, the gas density ρ_g decreases and the gas viscosity μ_g increases (Knowlton, 1999); ρ_g being inversely proportional to the absolute temperature T and μ_g being proportional to T^n , where n is usually between 0.6 and 1.0 (Wu and Baeyens, 1991). Unlike temperature, increasing the bed pressure P yields an increase in ρ_g (ρ_g being proportional to P) while μ_g remains essentially unchanged (Knowlton, 1999) when the system pressure is well below the critical pressure. The variations in the gas density and viscosity define the change in the magnitude of fluid forces acting on the particles at a given superficial gas velocity U_g .

Different types of IPFs can contribute to the net level of IPFs in a bed. Electrostatic and van der Waals forces are the most important types of IPFs when a gas-solid fluidized bed is operating in a dry environment (Shabaniyan et al., 2012). Other types of IPFs can be classified as originating from a material bridge, either liquid or solid, which could lead to a much stronger adhesive force between particles compared to the electrostatic and van der Waals forces (Seville et al., 2000, Shabaniyan et al., 2012). Since the electrical conductivity of particles increases with the temperature (Boggs et al., 2001, Jain and Saxena, 2009), the magnitude of electrostatic forces decreases at higher thermal levels (Moughrabiah et al., 2009, Alsmari et al., 2015). The magnitude of van der Waals forces, however, increases with the temperature owing to the enhancement of the molecular dipole pulsation around the contact point between particles in mutual contact, i.e., a remarkable increase in the Hamaker constant, by thermal excitation (Krupp, 1967, Valverde, 2012). Increasing the bed temperature close to sintering causes an additional increase in the magnitude of van der Waals forces due to the larger interparticle contact area resulting from the viscous flattening of solid particles that occurs before sintering (Rumpf, 1977). A material bridge between the particles can form at elevated temperatures due either to the structural/chemical changes at the particle surface, e.g., sintering, crystallization, or plastic deformation, or to the formation/addition of a liquid (Pagliai et al., 2004). Sintering is characterized by the migration of holes/lattice cavities or the movement of atoms to a less dense area of the material on the surface of particles, i.e., the bond zone (Siegel, 1984). As described by Siegel (1984), it occurs due to surface or volume diffusion, viscous flow, vaporization, or a combination of these mechanisms yielding a solid-solid bond between the particles in contact at its final stage. A trace amount of liquid can form in a high temperature gas-solid fluidized bed under certain conditions. It can coat the surface of particles and subsequently generate liquid bridges at the contact points between particles. The presence of some elements/compounds with a low sintering temperature within the bed, which sinter/melt at elevated temperatures and further react with each other or other solids, can produce new compounds with a low melting temperature (eutectics) that are in liquid form under high temperature operating conditions (Tardos and Pfeffer, 1995). Particle stickiness/agglomeration due to the presence of liquid bridge is frequently experienced in high temperature gas-solid fluidized bed combustors/gasifiers of low rank coals, biomass, and wastes. The ash sintering and chemical reaction between the alkali/alkali earth metal elements in the solid fuels/ash and the bed materials, usually silica sand, are believed to be the sources of this phenomenon (Werther et al., 2000, Bartels et al., 2008, Van Caneghem et al., 2012). Gas adsorption onto the surfaces of solids due to high gas pressure increases the level of van der Waals IPFs (Rietema, 1991, Xie, 1997, Valverde, 2012). The role of IPFs in governing the fluidization behavior becomes critical if one of the IPFs is in the same order of magnitude as the weight of the particle (Bartels et al., 2008).

When the ratio of the magnitude of IPFs/HDFs is low and does not increase with the bed temperature and pressure, i.e., HDFs dominate the fluidization behavior, the modifications in the bed hydrodynamics under extreme conditions can be predicted by simply taking into account the variations in the gas properties. In this case, the opposing variations that can be experienced for each of the gas properties by changing the operating temperature and pressure should be integrated with the particle size information to determine if the modification in the fluidization behavior is governed by the inertia effect, viscous effect, or even a combination of the two. However, if the magnitude of IPFs is comparable with HDFs or higher at the desired operating conditions, the prediction of bed behavior becomes more complex. It is generally expected that IPFs can play a greater role in characterizing the bed hydrodynamics at elevated temperatures in comparison with high pressure conditions. This can be explained by the following two reasons: (i) as addressed above, the magnitudes of van der Waals and material bridge IPFs could increase with the bed temperature. These enhancements could reach a certain level where the magnitude of IPFs could easily overcome the magnitude of HDFs while it decreases with the temperature when fluidizing coarse particles or slightly increases for fine

particles. For instance, increasing the bed temperature from ambient to 1100°C decreases the gas density by a factor of 4.7 if the system pressure remains constant or increases the gas viscosity by a factor of 3–4 depending on the type of gas (Knowlton, 1999); (ii) a considerable increase in the level of HDFs could be achieved by increasing the bed pressure since the gas density increases by the same factor as the pressure ratio at identical temperatures (Knowlton, 1999). The increase in the level of HDFs by changing the operating pressure could be remarkably higher than what would be expected for the level of van der Waals IPFs through the accelerated gas adsorption. Therefore, the ratio of the magnitude of IPFs/HDFs could significantly decrease at elevated pressures. This argument also explains why pressurized gas-solid fluidized beds are preferred to process cohesive particles (Tsukada et al., 1993).

HYDRODYNAMICS OF A GAS-SOLID FLUIDIZED BED WITH NO IPFS OR A MINIMUM LEVEL THEREOF UNDER EXTREME CONDITIONS

The magnitude of IPFs is negligible in comparison with HDFs when particles with typical behaviors of Geldart group B and/or D powders are fluidized in a bed at ambient conditions and in a dry environment (Molerus, 1982). Thus, the magnitude of the ratio of IPFs/HDFs is at minimum for these powders under the abovementioned conditions. It can remain unchanged at elevated temperatures and pressures if no liquid phase is present in the bed, if the operating temperature is well below the sintering of particles, and if the gas adsorption onto solid surfaces due to high gas pressure yields a negligible increase in the level of van der Waals forces compared to the magnitude of HDFs at elevated pressures. Based on these considerations, the variation in the magnitude of fluid forces, principally the drag force, resulting from the changes in the gas properties is basically the only drift to be examined to determine the modification in the fluidization behavior of gas-solid systems with no IPFs or a minimum level thereof due to the change in operating conditions. Accordingly, to predict the bed hydrodynamics of a gas-solid system with no IPFs or a minimum level thereof at elevated temperatures and pressures, the variations in the gas properties should be taken into account in the hydrodynamic models/correlations that follow the correct trend of variations for the desired hydrodynamic parameters with respect to the operating temperature and/or pressure.

The drag force F_d on a single isolated particle, with particle diameter of d_p , in a uniform flow field is given by (Gibilaro, 2001):

$$F_d = C_d \frac{\pi d_p^2}{4} \frac{\rho_g U_g^2}{2} \quad (1)$$

where C_d is the drag coefficient, which can be calculated by the particle Reynolds number Re_p as follows:

$$C_d = \begin{cases} 24/Re_p & Re_p < 0.1 \text{ (creeping flow regime)} \\ (0.63 + 4.8/\sqrt{Re_p})^2 & \text{(all flow regimes)} \\ 0.44 & 500 < Re_p < 10^5 \text{ (inertial flow regime)} \end{cases} \quad (2)$$

For gas-solid systems for which the level of IPFs is minimal and remains unchanged under the operating conditions, investigating the value of Re_p helps to determine which variation in the inertial or viscous forces is a dominant change. Under the abovementioned classification for the gas-solid system, when coarse particles with typical behavior of Geldart group D powders at ambient conditions are adopted in the bed, the variation in the gas density determines the change in the fluidization behavior at elevated temperatures and pressures. It is due to the fact that Re_p for coarse particles is well beyond the creeping flow condition ($Re_p \ll 1$) where the viscous effect dominates over inertia (Bird et al., 2002, Shabaniyan et al., 2012). Therefore, increasing the bed temperature and pressure causes the magnitude of the drag force applied on the coarse particles to decrease and increase, respectively, and the bed behavior is consequently modified. Under the same classification for the gas-solid system, if moderate-sized particles with typical Geldart group B behavior at ambient conditions are employed in the bed, the magnitude of the drag force applied on the particles increases with the bed pressure and in turn governs the bed hydrodynamics. However, the simultaneous opposing variations in the gas density and viscosity due to an increase in the operating temperature, which will be reflected in the magnitude of the drag force, govern the modifications in the fluidization behavior of moderate-sized particles. The contribution of the inertia effect, i.e., a decrease in ρ_g due to temperature in this case, increases for larger particles. Nevertheless, if fine particles with the typical fluidization behavior of Geldart group A powders at ambient conditions are fluidized in the bed and if the level of IPFs remains relatively unchanged with the operating temperature, the drift in the drag force resulting from an increase in μ_g determines the change in the bed hydrodynamics. Therefore, the trend and extent of modifications in the bed flow dynamics of moderate-sized

particles with the classification defined above will be in-between those of coarse and fine particles. Critical findings about the effects of temperature and pressure on the fluidization behavior of gas-solid systems with a minimal level of IPFs are provided below. Interested readers are invited to review Shabanian and Chaouki (2017) for full details.

The minimum fluidization velocity U_{mf} increases as the temperature rises for larger particles of Geldart group D powders at ambient conditions, while the minimum fluidization voidage ε_{mf} is a very weak function of temperature for these powders (Botterill et al., 1982, Llop et al., 1995). For coarse particles behaving similarly to powders close to the group B/group D boundary based on Geldart's classification at ambient conditions and which undergo a fluidization behavior in the transition region between the viscous and inertia flow regimes, U_{mf} remains essentially insensitive to temperature and ε_{mf} experiences a slight increase with increasing temperature at atmospheric pressure (Llop et al., 1995, Formisani et al., 1998). When the bed pressure increases, since the influence of the inertia effect on U_{mf} becomes more deterministic compared to the viscous effect, U_{mf} increases with the temperature for these powders (Llop et al., 1995) while ε_{mf} keeps the same functionality with regards to temperature. For smaller particles of Geldart group B powders at ambient conditions, U_{mf} decreases and ε_{mf} slightly increases with the temperature (Botterill et al., 1982, Llop et al., 1995, Formisani et al., 1998). Increasing the bed temperature causes the bubble size d_b to decrease, while the bubble passage frequency remains relatively unchanged at a given U_g (Shabanian and Chaouki, 2016a), and the transition velocity from bubbling to turbulent fluidization regime U_c to increase (Cai et al., 1989).

Increasing the bed pressure has relatively no influence on ε_{mf} (Chitester et al., 1984) while for a gas-solid system with particles larger than about 200 μm , where the inertia effect begins to dominate over the viscous effect (Hoffmann and Yates, 1986), it yields a decrease in U_{mf} (Chitester et al., 1984, Olowson and Almstedt, 1990, Llop et al., 1995). Increasing the particle size promotes the influence of pressure on U_{mf} . When the bed pressure increases at identical excess gas velocities, $U_g - U_{mf}$, the fluidization behavior of moderate-sized and coarse particles can be further modified through a decrease in d_b (Hoffmann and Yates, 1986, Schweinzer and Molerus, 1987, Olowson and Almstedt, 1990), when $U_g - U_{mf}$ is not very low (Cai et al., 1994), and in the bubble stability (Hoffmann and Yates, 1986, Olowson and Almstedt, 1992). In contrast, increasing the bed pressure at a given $U_g - U_{mf}$ can cause an increase in the bubble coalescence and splitting rates (Hoffmann and Yates, 1986, Olowson and Almstedt, 1992) and the bubble passage frequency (Hoffmann and Yates, 1986, Schweinzer and Molerus, 1987, Olowson and Almstedt, 1990). In addition, an increase in the effective drag force applied on the moderate-sized and coarse particles at higher pressures results in a decrease in U_c (Yang and Chitester, 1988, Cai et al., 1989), choking velocity U_{ch} (Knowlton, 1999), and terminal velocity U_t (Yang and Chitester, 1988, Li et al., 2013) and an increase in the solids entrainment rate (Chan and Knowlton, 1984).

HYDRODYNAMICS OF A GAS-SOLID FLUIDIZED BED WITH IPFS UNDER EXTREME CONDITIONS

IPFs are always present in a gas-solid fluidized bed and the ratio of the magnitude of IPFs/HDFs is the most critical parameter that governs the bed hydrodynamics. Studying Geldart's classification of powders (Geldart, 1973) reveals that, when dealing with a gas-solid system in a dry environment, the ratio of the magnitude of IPFs/HDFs increases when moving from Geldart group D powders toward group C, refer to the fluidization behavior at ambient conditions, while the magnitude of IPFs is comparable with that of HDFs for fine powders with typical Geldart group A behavior at ambient conditions. As alluded to earlier, the ratio of the magnitude of IPFs/HDFs for a bed of given powders can decrease (e.g., for hard coarse particles in the absence of the liquid phase at high pressure) or increase (e.g., for soft materials and in the presence of the liquid phase at high temperature) by changing the operating conditions. Accordingly, a single adjustment of the gas properties for the operating conditions in the conventional hydrodynamic models/correlations, as discussed in the previous section, cannot adequately predict the hydrodynamics of a gas-solid fluidized bed with IPFs under extreme conditions. In order to achieve this goal, the variation in the magnitude of IPFs and its corresponding influence on the bed hydrodynamics must be taken into consideration together with that of the HDFs. This argument is not only valid for the gas fluidization of fine powders, which is impacted by the presence of IPFs even at near-ambient conditions, but can also be extended to the gas fluidization of moderate-sized and coarse particles at elevated temperatures and pressures if the magnitude of IPFs increases considerably, e.g., by the material bridge due to either the sintering of particles or the presence of eutectics in the bed, the plastic deformation of the particle surface at elevated temperatures or a significant increase in the level of van der Waals IPFs due to the gas adsorption at elevated pressures.

Ruling out the contribution of IPFs to the gas-solid fluidization behavior under extreme conditions when the ratio of the magnitude of IPFs/HDFs is not negligible is the main source of disagreement among researchers when analyzing the influence of operating conditions on bed hydrodynamics. Despite the fact that this debate principally results from the uncertain nature of IPFs involved in the system and the difficulty of measuring them directly (Yates and Lettieri, 2016), some reliable approaches can be employed to identify that an acceptable level of IPFs is present in a gas-solid fluidized bed under extreme conditions. They can be listed as follows: (i) a titling bed (Rietema and Piepers, 1990) can be applied to determine a condition, where the bed surface is not horizontal; (ii) measure the Hausner ratio (Geldart et al., 1984) and find values higher than one; (iii) measure the total bed pressure drop vs. U_g and look for a condition where an overshoot appears in the pressure drop profile at U_{mf} and intensifies upon changing the operating conditions, e.g., an increase in the bed temperature (Shabaniyan and Chaouki, 2015); (iv) the dilatometry measurement (Compo et al., 1987) can be attempted to determine the minimum sintering temperature as the level of adhesive IPFs dramatically increases at operating temperatures close to sintering; (v) compare the experimentally measured U_{mf} at different operating conditions with those predicted by conventional hydrodynamic models/correlations when the gas properties are corrected for the operating conditions and search for a condition where the measured values are deviating from the predicted ones. Once the presence of an acceptable level of IPFs is approved in a high temperature and/or high pressure gas-solid fluidized bed, the prediction of the drift that a specific hydrodynamic parameter can tolerate when the operating temperature and/or pressure increases is straightforward if the parameter experiences an identical change, i.e., either an increase or a decrease, due to an increase in the bed temperature and pressure and the level of IPFs. In contrast, the prediction of a modification in the hydrodynamic parameter becomes more complicated if temperature, pressure, and IPFs affect it differently. This condition is, unfortunately, far beyond our knowledge at this point. Hence, experimental investigations with the targeted powders at the desired operating conditions are required to provide reliable information about the extent and trend of variations in the bed hydrodynamics. Below, critical findings about the effect of IPFs on the fluidization behavior and the influences of temperature and pressure on the hydrodynamics of a gas-solid fluidized bed with IPFs are provided. More details are available elsewhere (Shabaniyan and Chaouki, 2017).

Enhancing the magnitude of IPFs yields an increase in the fixed bed voidage ϵ_0 and/or ϵ_{mf} (Rietema, 1991, Rhodes et al., 2001, Shabaniyan and Chaouki, 2014 & 2015) and U_{mf} (Lettieri et al., 2001, Espin et al., 2011, Shabaniyan and Chaouki, 2015 & 2016a). If particles with typical behavior of Geldart group B and/or D powders at ambient conditions are fluidized in the bed, the bed flow dynamics can change toward Geldart group A and/or even C behavior upon increasing the level of IPFs (Seville and Clift, 1984, McLaughlin and Rhodes, 2001, Rhodes et al., 2001, Shabaniyan and Chaouki, 2015). In the bubbling fluidization regime and at a given U_g , a slight increase in the level of IPFs in a bed of relatively coarse particles, e.g., larger particles of Geldart group B powders at ambient conditions, causes a slight decrease in d_b , bubble passage frequency, and the quality of solids mixing and an increase in the interstitial gas velocity. Also, U_c and the solids entrainment rate decreases and increases, respectively, with IPFs (Shabaniyan and Chaouki, 2014 & 2015). At a given U_g above the minimum bubbling velocity U_{mb} , a progressive increase in the level of IPFs while the bed is far enough from the defluidization conditions signifies the evolutions discussed above on the bed hydrodynamic parameters. In addition, enhancing the magnitude of IPFs up to an appreciable level, i.e., moderate/high level, increases the idle time (Shabaniyan and Chaouki, 2016b), i.e., the time that solids spend in the emulsion phase (Stein et al., 2000), and bubble growth rate with U_g (Shabaniyan and Chaouki, 2015). When a moderate level of IPFs is present in a bed, it contains smaller bubbles at low to moderate gas velocities in the bubbling regime in comparison to a system with no IPFs. However, larger bubbles are present in a bed with a moderate level of IPFs at gas velocities approaching U_c . This indicates that a trend inversion in d_b takes place at moderate gas velocities (Shabaniyan and Chaouki, 2015). The trend inversion point shifts toward lower gas velocities if the level of IPFs is further increased. In other words, upon increasing the level of IPFs up to a high level, larger bubbles can be present in the bed at all superficial gas velocities above U_{mb} (Shabaniyan and Chaouki, 2016a). An additional increase in the level of IPFs promotes the dynamic clusters that are present in the dense bed (Mostoufi and Chaouki, 2000) to change their entities to permanent agglomerates. In this regard, increasing the level of IPFs in the bed up to a very high level, which leads the bed to approach the complete defluidization state, advances bubble enlargement, and thus enhances the presence of oblong bubbles that function similar to channels in the bed. A critical review of the mechanism, detection, and prevention of agglomeration in a high temperature gas-solid fluidized bed has been completed by Bartels et al. (2008).

Fine particles that belong to Geldart group A powders at ambient conditions are naturally cohesive (Seville et al., 2000). When a fluidized bed of these powders operates at elevated temperatures, an increase in the

magnitude of the drag force due to an increase in μ_g with the increasing temperature principally determines the modifications in the fluidization behavior if the level of IPFs remains relatively unchanged under the conditions of interest. Hence, U_{mf} decreases with the operating temperature under this condition (Rapagna et al., 1994, Formisani et al., 1998). However, if the level of IPFs sensibly increases with the temperature, particularly when the bed temperature approaches the initial sintering temperature, U_{mf} experiences a trend inversion with the increasing temperature, i.e., experiences a minimum and subsequently increases at an accelerated rate with the operating temperature. Therefore, the experimental U_{mf} increasingly deviates from the purely HDF-based predictions. This can be observed from the experimental results of Zhong et al. (2012), which are adapted in Fig. 1. It shows that U_{mf} for fine iron powders, $74 < d_b < 149 \mu\text{m}$, decreased when they were fluidized by a more viscous gas ($\mu_{Ar} > \mu_{N_2} > \mu_{H_2}$) and the trend inversion in U_{mf} as the temperature rose occurred at a higher temperature for the gas with a higher viscosity. Fig. 2 reports the results of dilatometry measurements that were carried out in a nitrogen environment for the fine iron powders. It indicates that these powders could sinter at 644°C , which is in broad agreement with the results provided in Fig.1.

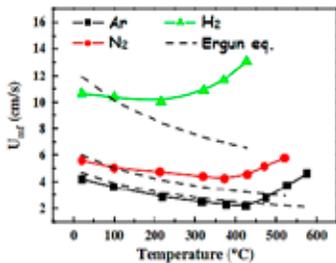


Fig.1. Dependence of U_{mf} on temperature for iron powders ($74 < d_b < 149 \mu\text{m}$) in different gases. Adapted from Zhong et al. (2012).

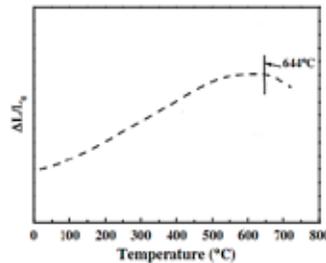


Fig.2. Elongation-contraction of fine iron powders ($74 < d_b < 149 \mu\text{m}$) in a nitrogen environment. Adapted from Zhong et al. (2012).

Increasing the operating temperature in a bed of fine powders increases ε_0 and/or ε_{mf} , which was attributed to the thermal enhancement of IPFs (Yamazaki et al., 1986, Formisani et al., 1998 & 2002). Also, operating a gas-solid fluidized bed of fine powders at elevated temperatures causes an increase in d_b , the bubble passage frequency (Cui and Chaouki, 2004), and the interstitial gas velocity (Formisani et al., 2002) in the bubbling regime and at a given U_g , a decrease in U_c (Cai et al., 1989, Cui and Chaouki, 2004), and an increase in the solids entrainment rate (Findlay and Knowlton, 1985) when the role of IPFs is not well pronounced.

Increasing the bed pressure in a bed of fine powders has relatively no effect on U_{mf} and ε_{mf} (King and Harrison, 1980, Chitester et al., 1984). The former drift is due to the fact that these powders undergo fluidization in the viscous flow regime and μ_g is a very weak function of the gas pressure (Knowlton, 1999). An increase in the operating pressure at identical U_g in a bubbling bed of fine powders increases the bubble coalescence and splitting rates (Barreto et al., 1983), bubble passage frequency (Barreto et al., 1983, Chan et al., 1987), and interstitial gas velocity (Weimer and Quarderer, 1985) and decreases d_b (King and Harrison, 1980, Barreto et al., 1983, Weimer and Quarderer, 1985, Chan et al., 1987) and bubble stability (King and Harrison, 1980). In addition, operating a gas-solid fluidized bed of fine powders at high pressure yields a decrease in U_c (Yang and Chitester, 1988, Cai et al., 1989, Tsukada et al., 1993) and U_{ch} for a constant solids mass flux (Karri and Knowlton, 1996) and an increase in the solids entrainment rate at a given U_g (Yang and Chitester, 1988).

SUMMARY

Since most industrial processes employ gas-solid fluidized beds under extreme conditions, a reliable prediction of fluidization behavior under similar operating conditions is critical. To this end, the relative importance of IPFs and HDFs in governing the bed hydrodynamics must be properly identified. However, owing to the great complexity of IPFs and the unavailability of a measurement technique that can adequately determine their extent under extreme conditions and, hence, assist in quantifying the corresponding influence on the bed behavior, our understanding about the bed hydrodynamics at elevated temperatures and pressure is still far from complete. Despite these challenges, a few reliable approaches, as alluded to earlier, can be adopted to identify if the system is/will be operating under the influence of IPFs at the desired operating conditions or not. In cases where HDFs are governing the fluidization behavior, i.e., IPFs are at a minimum, the bed flow dynamics can be predicted by adjusting the gas properties in appropriate hydrodynamic models/correlations

that follow the right trend of variations for the hydrodynamic parameters with respect to the operating temperature and/or pressure. Nevertheless, if the importance of IPFs cannot be neglected, the variations in the magnitudes of HDFs and IPFs and the corresponding impacts on the fluidization behavior must be taken into account concurrently, which makes the prediction challenging, particularly when temperature, pressure, and IPFs have different effects on the bed behavior. Under these circumstances, experimental investigations with the targeted powders at the desired operating conditions are recommended to shed light on the effect of process conditions on bed hydrodynamics. Moreover, a fluidization study at high temperature and pressure simultaneously is required to provide a full understanding of the effect of operating conditions on bed hydrodynamics.

NOTATION

Acronyms

HDFs hydrodynamic forces
IPFs interparticle forces

Symbols

C_d drag coefficient [-]
 d_b bubble size [m]
 d_p particle diameter [m]
 F_d drag force [N]
 n power of absolute temperature; $\mu_g \propto T^n$,
0.6 < n < 1.0 [-]
 P pressure [kPa]
 Re_p particle Reynolds number [-]
 T absolute temperature [K]

U_c transition velocity from bubbling to turbulent
fluidization regime [m/s]
 U_{ch} choking velocity [m/s]
 U_g superficial gas velocity [m/s]
 U_{mb} minimum bubbling velocity [m/s]
 U_{mf} minimum fluidization velocity [m/s]
 U_t terminal velocity [m/s]
 $U_g - U_{mf}$ excess gas velocity [m/s]

Greek letters

ε_0 fixed bed voidage [-]
 ε_{mf} minimum fluidization voidage [-]
 μ_g gas viscosity [Pa.s]
 ρ_g gas density [kg/m³]

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