The Effects of Thermally Induced Interparticle Forces on the Expansion and Bubbling Behaviour of a Fluidized Bed

Rossella Girimonte[*]   Bruno Formisani[†]

[*]Università di Calabria, Italy, rossella.girimonte@unical.it

[†]Università di Calabria, Italy, bruno.formisani@unical.it

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Rossella Girimonte and Brunello Formisani
Dipartimento di Ingegneria Chimica e dei Materiali, Università della Calabria
I 87036 Arcavacata di Rende (Cosenza), Italy
T: +39-0984-496689; F: +39-0984-496655; E: rossella.girimonte@unical.it

ABSTRACT

The paper addresses the transition to the bubbling regime of solid beds belonging to Geldart's group A, from ambient temperature to 500°C. The analysis of the influence exerted by operating temperature on the variables that characterize both the homogeneous expansion of the bed and the onset of a steady bubbling regime is conducted on the fluidization map of the fluidized bed, namely the voidage-velocity diagram into which results of the fluidization and bed collapse experiments are merged.

The results obtained show that at elevated temperatures the ability of the fluidized bed to preserve the homogeneous fluidization regime is extended to unusually high voidage levels. Even past the appearance of a steady bubble flow, the dense phase voidage exhibits a residual dependence on interparticle forces induced by high temperature.

INTRODUCTION

According to Geldart classification, at ambient conditions only solids of group A are able to exhibit a state of homogeneous fluidization prior to bubble formation, in which the bed expands smoothly in response to any increase of gas velocity and behaves like a low viscosity fluid ([1](1)). The peculiarity of this regime has been explained by most authors with the existence of cohesive forces which act at the interparticle contact points whose intensity becomes as much comparable to that of mass forces as particle size reduces.

With regard to that, Rietema ([2](2)) stated that a major effect of the presence of interparticle forces in a fluidized bed is that of stabilizing its homogeneous structure against little disturbances, as if it were endowed with an effective elastic modulus that makes the bed similar to a weak solid rather than a fluid-like system. On the other hand, Foscolo and Gibilaro ([3](3)) rejected this view and assumed the bed as composed by an assembly of free-floating particles whose expansion can be predicted according to a stability criterion based on the dependence of the gas-particle drag on bed voidage.

On investigating self-diffusion in gas-fluidized beds of fine powders, Valverde *et al.* (4) have tried to clarify this apparent controversy. Their experiments suggest the existence of two distinct regimes in the velocity range of homogeneous expansion. Past the minimum fluidization threshold and up to a critical value of velocity (lower than the minimum bubbling value), the bed behaves like a weak solid: no mixing is observed and the bed is characterized by a yield strength that helps it to preserve its static properties. Over this critical velocity up to the minimum bubbling point, the yield strength of the bed vanishes, so that it behaves like a fluid subjected to diffusion dynamics.

Although it is typical of A solids fluidized at room conditions, particulate expansion has been observed also in fluidization of coarser particles at superambient pressure or temperature. At the same time, previous studies on the transition from the fixed to the incipiently fluidized state at elevated thermal levels have shown that rising the operating temperature of fluidization enhances the role of interparticle forces within the solid bulk up to a level at which bed defluidization eventually ensues (5-7).
These findings seem to establish a similarity with the fluidization properties of fine particles; on this basis, the presence of significant cohesive forces in a particle bed fluidized at high temperature should visibly affect its route to the bubbling regime. Verifying the nature of this influence by analyzing the expansion properties of several solid beds is, therefore, the objective of this study.

EXPERIMENTAL APPARATUS AND MATERIALS

The experimental investigation, based on fluidization and bed collapse tests, has been performed in a transparent quartz column 5 cm ID, located in an electrically heated furnace whose regulation was provided by a PID temperature controller driven by a thermocouple immersed in the bed.

Table 1.   Properties of the experimental solids.

	FCC 63-90 μm	FCC 90-125 μm	Silica Sand 63-90 μm	Silica Sand 90-125 μm	Corundum 63-90 μm
Particle density, ρ_p [kg m^{-3}]	1400	1400	2620	2620	4000
Sauter diameter, d_p [m]	76·10^{-6}	96·10^{-6}	79·10^{-6}	100·10^{-6}	67·10^{-6}
Sphericity, ϕ_p [-]	0.99	0.99	0.61	0.55	0.56
Minimun fluidization velocity at 30°C, u_{mf} [cm s^{-1}]	0.49	0.65	0.71	1.22	0.98
Terminal velocity at 30°C, u_t [cm s^{-1}]	20.5	30.2	13.8	20.7	13.0
Richardson-Zaki exponent at 30°C, n [-]	4.61	4.34	4.74	4.65	4.77

The column is optically accessible through a vertical window in its insulating shell, so that a videocamera connected to a tape recorder can be used to register bed heights during fluidization and collapse tests, for later analysis. During bed collapse experiments two solenoid valves are employed, commanded by the same switch to ensure simultaneous action; the first valve abruptly cuts the air feed off, while the second one gives vent to air trapped in the column wind-box, thus preventing any residual gas flux through the particle bed.

At any operating condition (i.e. temperature and operating velocity), the collapse

curve of the bubbling bed provides data of the total bed height, H_b, of the dense
phase height, H_d, as well as of the height of the fixed bed at rest, H_0. From them,
values of the corresponding bed voidages conditions are obtained as

$$\varepsilon = 1 - \frac{m}{H \rho_p A} \tag{1}$$

where m and A are the bed mass and section, respectively.

The error associated to these readings is not larger than $\pm\,0.5$ mm, so that the
uncertainty in bed voidage calculations never exceeds 1%. Full details of the data
processing procedure are given in a previous paper (8).
Five solids of the group A of Geldart, namely two cuts of FCC, two of silica sand and
one of corundum, have been subjected to experiments, at temperatures which
ranged from room level to 500°C. The properties of these are listed in Table 1.

RESULTS

The procedure for locating the minimum bubbling point used in this study is derived
from the analysis of the expansion behaviour of the bed over a range of fluidization
velocities as wide as to span from the fixed bed state to the freely bubbling regime.
At relatively low velocities, values of ε_b are calculated from data of bed height
determined during the experiment of fluidization; at higher velocities, instead,
determination of bed voidage is achieved by working out the kinetics of collapse of
the fluidized bed, a method capable of providing both the overall bed voidage ε_b
(whose value is affected by the presence of bubbles) and that of the dense phase,
ε_d. Plotted together on the same diagram versus fluidization velocity, the two sets of
data allow reconstructing what has been called the "fluidization map" of the particle
system (9), that provides a comprehensive representation of the transition to the
bubbling regime.

Expansion diagrams

Fig.1 reports three different types of fluidization maps, which illustrate the different
expansion behaviours exhibited by the solids referred to in this paper at 30, 200 and
500°C. Their analysis shows how, after that particle suspension has been achieved
at u_{mf}, ε_b (solid lines) increases in a nearly linear way until a peak (Fig.1A), a plateau
(Fig.1B) or a visible change of slope (Fig.1C) occurs. Each of these points
corresponds to the velocity value u_e at which the homogeneous expansion of the bed
comes to an end and occasional bubbles or cracks in the solid mass are first
observed which give place, for moderate increases of the gas velocity , to an
irregular shortcut for the excess flow rate. Therefore, the velocity u_e has to be
considered to mark the end of homogeneous expansion rather than being a true
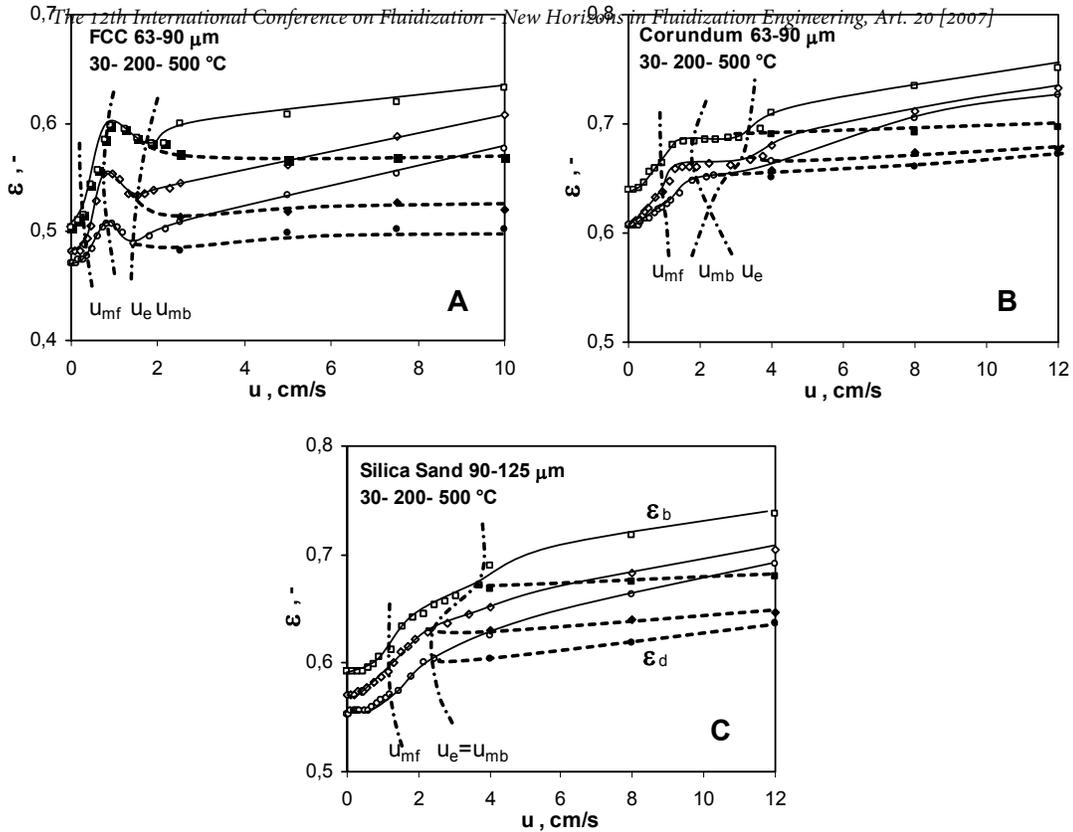measure of the minimum bubbling velocity of the bed.

Fig.1 - Bed fluidization maps at varying temperature.

However, each of these diagrams shows also the existence of a higher velocity which represents the threshold at which a regular bubble swarm (rather than some isolated bubbles) starts to travel across the emulsion phase of the bed. On the diagrams of Fig.1 this velocity is called u_{mb} and corresponds to the point at which the curves of ε_b and ε_d diverge. u_{mb} is thus located at the minimum of the ε_b curve, at the end-point of its plateau or is coincident with the one which fixes u_e of systems whose fluidization map is similar to Fig.1C. Beyond u_{mb} the voidage of the emulsion phase remains nearly unchanged (FCC) or slightly increases (silica sand and corundum), thus indicating that the dense and the bubble phase of the bed have attained a stable structure.

For all materials, fluidization maps show that the tendency of ε_d to achieve a constant value is typical of high temperatures, as found also with solids like FCC whose dense phase undergoes a visible contraction during the transition to the bubbling regime.

The dependence of voidage and velocity parameters on T

On reporting the dependence on operating temperature of ε_{mf}, ε_e, ε_{mb} and ε_d, Fig. 2 shows distinct series of results which illustrate the differences of behaviour of the solids under investigation during their transition to the freely bubbling regime.

Past incipient fluidization, both cuts of FCC (of which only 63-90 μm cut is shown) undergo a particulate expansion that brings them to the maximum voidage ε_e and then stabilize themselves on a lower voidage value ε_{mb} as soon as bubbling becomes steady. A higher velocity is however required for the dense phase of the bed to complete its contraction, so that at the end of this transient ε_d, albeit higher than ε_{mf}, is always lower than ε_{mb}. This characteristic behaviour is maintained at all temperatures so that the curves of the various voidage parameters are clearly distinct from one another all over the temperature field (Fig.2A).

Something different is observed with solids of higher density, like corundum and silica sand, referred to in Figs 2B and 2C, respectively (data of silica sand 63-90 μm, quite similar to those of the 90-125 μm cut, are not reported). The voidage ε_e achieved at the end of homogeneous expansion is practically constant throughout the transient that leads, after the appearance of some occasional gas pocket in the particle mass, to the development of a steady flow of bubbles. Therefore, all over the temperature range investigated, curves of ε_e, ε_{mb} and ε_d are all coincident well above the ε_{mf} level.
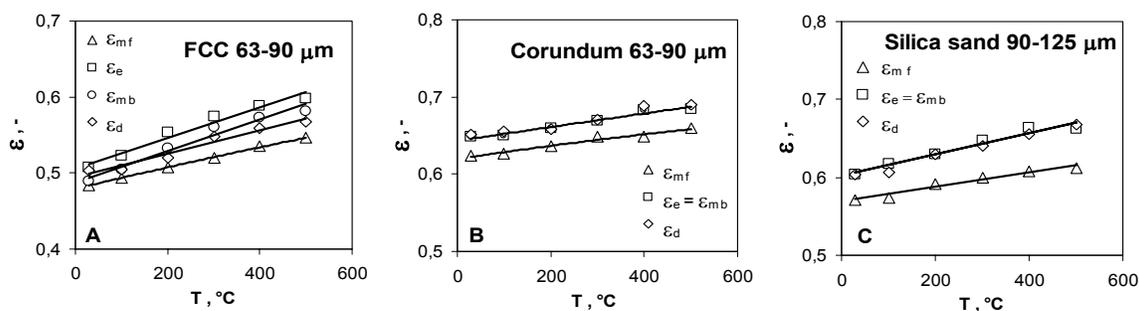

Fig.2 - Bed voidage parameters at varying temperature.

The effectiveness of high temperature in causing the increase of system voidage has been already verified and discussed in previous studies with reference to the packed and the incipiently fluidized state (5,8) and will not be recalled here. Present results confirm that also other voidage parameters, such as ε_e, ε_{mb} and ε_d exhibit the same type of dependence on T. As a matter of fact, whatever the value of ε_{mf} at ambient temperature (exceeding 0.6 for highly non-spherical particles), all solids prove able to achieve even higher porosities in consequence of their particulate expansion. Moreover, as far as the difference ε_e-ε_{mf} is concerned, the expansion ability of each bed is practically unaffected by fluidization temperature.

However, if the value of the minimum bubbling voidage is taken as that at which the presence of bubbles becomes a stable feature of bed behaviour, it is found that a solid like FCC is not able to keep its dense phase structure under the disturbing action of bubbles, so that both ε_{mb} and ε_d result systematically lower than ε_e and shifted from the ε_{mf} line. As a major difference from this behaviour, the dense phase of beds of silica sand and corundum maintains the porosity achieved at the point of maximum expansion, as witnessed by the coincidence of ε_e, ε_{mb} and ε_d at all temperature levels.

Further considerations are suggested by the corresponding velocity diagrams, *The 12th International Conference on Fluidization - New Horizons in Fluidization Engineering, Art. 20 [2007]*
reported in Fig. 3. Here, with exception of silica sand 90-125 μm which exhibits the equal values of u_e and u_{mb}, the dependence on T of the velocity limit of particulate expansion, u_e, is not too different from that of u_{mf}, so that the two curves are always nearly parallel, a fact that reflects the similarity of the lines of ε_e and ε_{mf}. That demonstrates that the region of particulate expansion of these systems is unaffected by the thermal level of fluidization.
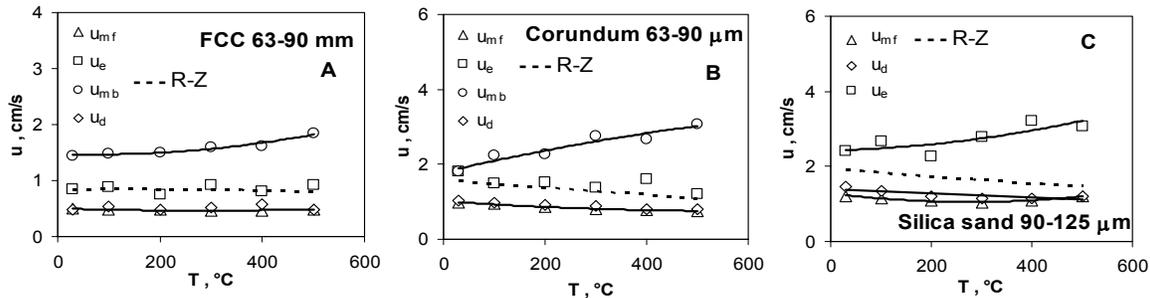

Fig.3 - Velocity parameters at varying temperature.

At the same time, not only u_{mb} of all beds increases along the whole temperature field, but it results higher or equal to u_e even when ε_{mb} is lower than ε_e.

Values of u_e of all solids have been compared with the predictions provided by the classical equation of Richardson-Zaki (Fig.3, dashed lines)

$$u_e = u_t \varepsilon_e^n \tag{2}$$

in which both n and u_t are functions of the terminal Reynolds number, which varies with T due to the variation of gas density and viscosity. With the exception of silica sand 90-125 μm, the agreement with data (including those of FCC 90-125 μm and silica sand 63-90 μm, not reported in Fig.3) seems to point out that, once that the experimental values of bed voidage are accounted, the relationship between gas velocity and bed porosity does not result different from that in common use at room conditions.

DISCUSSION

The results illustrated so far, relevant to the influence exerted by fluidization temperature on the transition to the bubbling regime of beds of fine solids, demonstrate the opportunity of locating the minimum bubbling velocity of these systems at the point at which a steady flow of bubble is first established. Once that this definition is accepted, the excess velocity $u_{mb}-u_{mf}$ results in all cases an increasing function of T.

In no case, anyway, is the thermal increase of this velocity difference attributable to a growing ability of particle systems to expand homogeneously in response to the increase of the gas velocity, as demonstrated by the fact that curves of u_e at varying T, consistent with predictions of eqn (2), are always nearly parallel to those of u_{mf}.

From the packed bed state to the end-point of particulate expansion, the major effect of the influence of high temperature on fluidization phenomenology is that of causing a generalized increase of all voidage parameters. The thermal variation of ε_{mf} and ε_e, practically linear for all solids, reflects that of the packed bed voidage ε_0 determined by previous investigations (5,8), that can be explained only by admitting the thermal enhancement of interparticle forces. Accounting for the thermal variation of ε_{mf} and ε_e is sufficient to preserve the capability of equations like Ergun's and Richardson-Zaki's to predict crucial parameters of fluidized bed dynamics such as incipient fluidization and particulate expansion.

Since, however, the velocity interval u_e-u_{mf} along which particulate expansion has place is practically unaffected by T, the increase of the excess velocity u_{mb}-u_{mf} with temperature must be attributed to that of the difference u_{mb}-u_e, specifically related to the transient from the end of expansion to steady bubbling.

To this regard, Fig.4 shows the relationship between system voidage and gas velocity (namely the ordinates of Figs 2 and 3) in either region. As far as u_e is considered (Fig.4A), its dependence on ε_e may be that of an increasing, decreasing or constant function. Hence, although the maximum voidage reached by bubble-free expansion increases at high temperature, its achievement does not necessarily require higher gas velocities, as the growth of gas viscosity proves sufficient to enhance bed expansion.
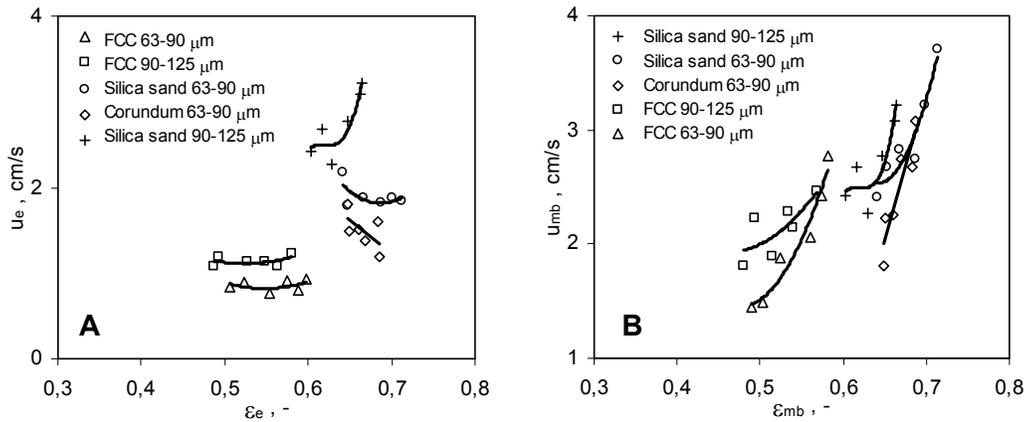

Fig.4 - The relationship between gas velocity and bed voidage: A) maximum homogeneous expansion; B) minimum bubbling condition

On the contrary, for regular bubbling to be established in any particle bed, the excess gas velocity required is generally an increasing function of operating temperature, an evidence of the growing difficulty encountered in altering the structure of the bed to allow the presence of the bubble phase.

Altogether, the role played by thermally induced interparticle forces in delaying the completion of the transition to the bubbling regime seems to be the common feature of the particulate systems examined in this paper and is in line with what observed by other authors on dealing with finer particles at ambient conditions (10). For none of these beds is the appearance of the bubble phase followed by the return of the

particulate emulsion to the minimum fluidization voidage, a circumstance that gives further confirmation of the persistency of interparticle thermal cohesion in the fluid-like bubbling regime.

CONCLUSIONS

Thermally induced interparticle forces influence the transition to the bubbling regime of beds of relatively fine particles that undergo fluidization at elevated temperatures. Measured in terms of voidage variation, the homogeneous expansion of these beds results practically unaffected by T, even if it can bring the particle system to porosity levels much higher than those experienced at room conditions. In most cases, the expansion process is well described by Richardson-Zaki's correlation, up to its upper velocity boundary u_e, identified by a peak, a plateau or a marked change of slope on the expansion diagram of the bed.

On the same diagram, the velocity u_{mb} can be traced at which a stable bubble phase begins to travel across the particle mass. The excess gas velocity $u_{mb}-u_e$ is related to the transition from the expanded state to the bubbling regime and is an increasing function of fluidization temperature.

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