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# Investigating the effect of segregation of particles and pressure gradient on the quality of fluidisation at sub-atmospheric pressures

Apurv Kumar [a,*], Peter Hodgson [a], Weimin Gao [a], Subrat Das [b], Daniel Fabijanic [a]

[a] Institute for Frontier Materials, Deakin University, 3216 Australia
[b] School of Engineering, Deakin University, 3216 Australia

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ABSTRACT

Degradation in quality of fluidisation for Group B powders under vacuum conditions occurs due to an existence of a fluidisation interface that separates the bubbling and static bed near the minimum fluidisation conditions. The significant pressure gradient existing due to bed weight and the particle segregation mainly affects the quality. The aim of the present work is to investigate the relative contribution of the pressure gradient and the presence of the segregation on the quality of fluidisation in vacuum conditions. Further, the effect of morphology of the particles on fluidisation quality is also studied. In addition, fluidisation maps are also obtained that reveal the optimal area of operation for enhanced heat and mass transfer processes. The results indicate that the travel of interface in the bed is affected only when the level of segregation in the bed is high. For intermediate and minimal disparity in size, the quality degradation is caused by the presence of sharp pressure gradient. Changing the morphology of the particle also altered the fluidisation characteristics of the bed and improved the quality significantly.



## 1. Introduction

Fluidized beds have been readily operated under varying pressure conditions apart from the atmospheric pressure. High pressures in fluidized beds affects the minimum fluidization velocity, bubble size and bubble dynamics in the bed [1–3]. Increased heat and mass transfer (relative to atmospheric) have also been observed in a bed of coarse particles when operated at high pressure [4]. In addition, many researchers have studied vacuum fluidisation, which is characterised by the presence of slip flow where the Knudsen number ($Kn = \lambda/d_p$) lies in the range of 0.01–1 [5–11]. The presence of slip flow affects the quality of fluidisation for powders with different particle density and size, generally classified under Geldart's groups. In low-pressure conditions, the existence of non-homogeneous fluidisation where an interface exists that differentiates the quiescent bed and the bubbling bed in proximity to the minimum fluidisation conditions has been reported [12–14]. Despite these observed quality issues, fluidisation under vacuum has been shown to be advantageous in various applications such as drying of pharmaceutical products, extractive metallurgy, CVD [10,11,15].

Segregated fluidisation in atmospheric conditions occurs when a bed has a broad particle size range, forming a horizontal interface that separates the lighter (flotsam) and the heavier particles (jetsam) [16]. The bed thus fluidises non-homogeneously with increase of flow rate. Group B powders (size, density) under vacuum have been found [7] to exhibit dual fluidisation zones (quiescent and fluidising) separated by a fluidisation interface in proximity to the minimum fluidisation conditions. In contrast, a bed Group A powders (size, density) fluidised under low pressure conditions exhibit smooth and interface-free fluidisation [7,17].

The existence of the horizontal interface in vacuum fluidisation is also attributed to the presence of a similar order of magnitude of the top pressure and the pressure drop through the bed [8,11]. The pressure gradient inside the fluidised bed (due to the weight of the particles) becomes significant when the operating pressures are reduced below atmospheric and this pressure gradient results in an acute velocity gradient causing the fluid to expand inside the bed [11]. Non-homogeneous fluidisation has therefore been ascribed to the inefficiency of the fluid to transfer momentum to the particles. However, numerous vacuum fluidisation studies have used powders with a continuous range of particle sizes [8,11–13,17]. Therefore, it is difficult to ascertain if the observed low quality fluidisation under vacuum is due to the segregation phenomenon magnified by the presence of vacuum or an inherent incapability of vacuum condition to fluidise the entire bed simultaneously or a combination of both.

The aim of the present work is to investigate the relative contribution of powder segregation and the bed pressure gradient to the sub-atmospheric fluidisation quality. Alumina powders consisting of narrow and wide size distribution classified as Geldart's Group B were used in the present investigation. In addition, porous alumina is investigated in order to understand the effect of particle morphology on the fluidisation quality under vacuum. Quantification of the fluidisation

* Corresponding author at: na building, GTP, Waurn Ponds campus, Geelong, Australia. Tel.: +61 5227 3360.
*E-mail address:* apurv@deakin.edu.au (A. Kumar).

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quality of the powders was achieved by monitoring the progression of the fluidisation interface through the bed at different sub-atmospheric pressures. A proposed fluidisation quality index compares the behaviour of the various powders under vacuum condition. Further, fluidisation maps were constructed for all the powders, which are used to study the variation in the available optimal bubble space with pressure. These maps are highly useful for carrying out heat and mass transfer processes in cases where visualisation of the fluidisation phenomenon is unavailable due to the setup limitations.

## 2. Experimental method

### 2.1. Low-pressure fluidisation

A cylindrical fluidised bed made of polycarbonate and of size 50 mm ID and 1 m length was used having a porous sintered steel disc as a distributor plate (Fig. 1). The vacuum in the chamber was controlled by using bypass needle valves. Variable area flow meters with an accuracy of ±3% were used to measure air flow rate to the vacuum chamber. To ensure correct mass flow meter readings a pressure of 50 KPa was maintained on entry and exit side of the flow meter using a two-stage needle valve configuration. Pressure transducers with an accuracy of 0.25% were used to measure the pressures at two locations inside the chamber: 5 mm above the distributor plate and 5 mm below the exit of the chamber. In order to maintain consistency in results, similar inlet conditions (Table 1) were used in all experiments. The pressure data were acquired (10 Hz) by using ALMEMO 2590 data logger and were analysed offline by using a personal computer. The powders were analysed for size distribution by Malvern Mastersizer 2000, which utilises the technique of laser diffraction to measure the size of particles. It does this by measuring the intensity of light scattered as a laser beam passes through a dispersed particulate sample. This data is then analysed by the device to calculate the size of the particles that created the scattering pattern. Table 1 reports the d(0.1), d(0.5) and d(0.9) particle sizes for various powders used in the present work.

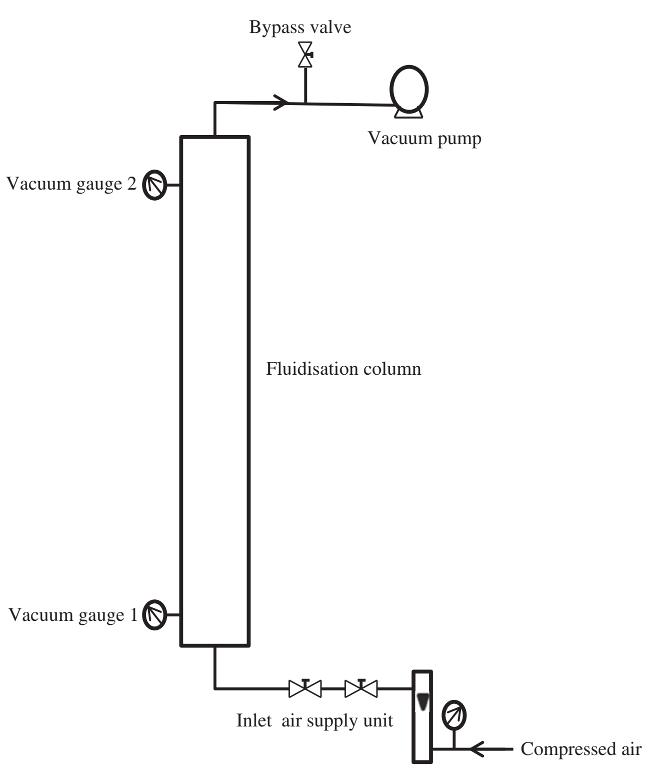


**Fig. 1.** Schematic diagram of vacuum fluidised bed used for experiments.

**Table 1**
Operational parameters and powder characteristics.

| | |
|---|---|
| Inlet pressure | 50 kPa |
| Inlet temperature | 27 °C |
| Inlet flow rate | 100–10,000 cc/min |
| Bed height | 440 mm |
| Bed diameter | 50 mm |
| Vacuum pressure | 1000–15 mbar |
| Alumina powder density | 3800 kg/m$^3$ |
| Porous alumina density | 800 kg/m$^3$ |

| Powder type | d(0.1) (μm) | d(0.5) (μm) | d(0.9) (μm) | Diameter ratio ($d_r$) |
|---|---|---|---|---|
| Alumina | 49.284 | 79.199 | 125.427 | 1.59 |
| | 67.265 | 103.260 | 157.726 | 1.53 |
| | 109.160 | 170.638 | 264.064 | 1.55 |
| Porous alumina | 55.032 | 84.056 | 127.922 | 1.52 |
| Mixture 1 | 59.404 | 116.806 | 275.145 | 2.22 |
| Mixture 2 | 62.124 | 153.69 | 550.148 | 3.46 |

### 2.2. Powder characteristics

Porous alumina and alumina powders were used for the current investigation, which are widely used for heat transfer applications in solid–gas fluidisation. Three sets of alumina powders were used that had narrow size distribution and varying median diameters, $d_p(0.5)$: 80, 103 and 170 μm. Fluidisation studies were performed on these powders and on mixtures of these powders (Mixture 1 and Mixture 2) to study segregation effect on quality. The size distribution for these powders accompanied by their respective SEM image is shown in Fig. 2. The properties of the powders and inlet conditions are given in Table 1. It can be seen that the alumina powders are irregular faceted particles and are classified as Group B powders. The porous alumina powders have minute pores throughout the structure ranging from 4 to 10 nm. This porosity greatly reduces the density of the alumina particles, relative to the monolithic alumina. Correspondingly, the weight of the bed is reduced; how this affects the pressure gradient in the bed and the resulting fluidisation quality is of interest.

### 2.3. Powder segregation classification

In order to study the effect of segregation on the quality of fluidisation, the particles are classified by using the pressure drop curves as Type A–E according to the segregation behaviour reported by Rao et al. [18]. Here powders are characterised by the density and size ratios of the jetsam and flotsam particles found in a mixture. In the present analysis, the jetsam and flotsam particles are considered as particles of size corresponding to the average of d(0.9) and d(0.5); d(0.5) and d(0.1), respectively. Similar averages of particle diameters have been used earlier [19,20] as jetsam and flotsam diameters in segregation analysis of particle size distribution powders. The result discussed in Section 4.1.2 justifies the classification of powders based on Rao method as minimal, intermediate and high segregation. The density and size ratios are thus defined as $\rho_r\left(=\frac{\rho_{jetsam}}{\rho_{flotsam}}\right)$ and $d_r\left(=\frac{d_{jetsam}}{d_{flotsam}}\right)$, respectively. Velocity ratio is defined as $U_r=\frac{U_{mf-jetsam}}{U_{mf-flotsam}}$. As all alumina particles belonging to Geldart's Group B have similar density, $\rho_r$ is unity in the present case. The size ratio, $d_r$, for 80, 103 and 170 μm is 1.58, 1.527 and 1.547, respectively. $d_r$ for Mixture 1 is 2.22. According to Rao et al. [18] the following are the powder classification (Type A–D):

Type A mixtures: Very large particle size ratio ($d_r > 4.5$, $U_r > 8$)