Abstract—The aim of this study is to determine minimum fluidization velocity of three different particles which represent different Geldart classification groups and to compare the results with computational results. The experiments were conducted using a fluidized cylindrical cold bed with uniform air distribution. The three particulate materials use were zirconia, bronze, and steel, classified as Geldart A, B and D particles, respectively, and the minimum fluidization velocities were found to be 0.015, 0.07 and 0.27 m/s, respectively. Using the commercial CPFD software Barracuda, the fluidized system was simulated using the Wen-Yu and Wen-Yu-Ergun multiphase flow models. The CPFD-determined minimum fluidization velocities for zirconia, bronze, and steel were found to be 0.008, 0.08 and 0.23 m/s, respectively, corresponding quite well with the experimental results for Geldart B and D particles.

Index Terms—Barracuda, fluidization, Geldart classification, minimum fluidization velocity, pressure drop, Wen-Yu, Wen-Yu-Ergun.

I. NOMENCLATURE

\[ D = \text{Drag function} \ [1/s] \]
\[ F_p = \text{Particle drag force} \ [N] \]
\[ g = \text{Gravitational acceleration} \ [m/s^2] \]
\[ m_p = \text{Particle mass} \ [kg] \]
\[ p = \text{Fluid pressure} \ [N/m^2] \]
\[ Re = \text{Reynold’s number} \]
\[ r_p = \text{Particle radius} \ [m] \]
\[ t = \text{Time interval} \ [s] \]
\[ u_p = \text{Particle velocity} \ [m/s] \]
\[ V_p = \text{Particle volume} \ [m^3] \]
\[ x = \text{Particle position} \ [m] \]
\[ y = \text{Restitution coefficient} \ [-] \]
\[ \theta_{cp} = \text{Particle volume fraction at close pack condition} \]
\[ \theta_f = \text{Fluid volume fraction} \ [-] \]
\[ \theta_p = \text{Particle volume function} \ [-] \]
\[ \mu_f = \text{Fluid viscosity} \ [Pa*s] \]
\[ \rho_f = \text{Fluid density} \ [kg/m^3] \]
\[ \rho_p = \text{Particle density} \ [kg/m^3] \]
\[ \bar{\rho}_p = \text{Average particle density} \ [kg/m^3] \]
\[ \tau_f = \text{Fluid stress tensor} \ [N/m^2] \]

II. INTRODUCTION

The fluidized bed is one of the best-known solids-gas contacting methods used in the processing industry, for instance in fluidized bed combustion or reaction systems involving solid catalysts. Basically, fluidization is achieved by sending a pressurized fluid through the particulate medium.

The main application of fluidization related to this study is separation of different particulate materials applied in CO₂ capture by calcium looping with indirect calciner heat transfer [1] using hot inert alumina particles to transfer heat to a sorbent made of calcium carbonate, hence facilitating calcination to calcium oxide and CO₂.

The zirconia material is based on downscaling CaCO₃ particles from hot-flow pilot-scale to cold-flow lab-scale conditions, whereas the steel and bronze particles are based on downscaling two different sizes of the alumina particles. Information about the minimum fluidization velocities, and the behavior of the particles before, during and after the minimum fluidization conditions, is crucial for the design of the above-mentioned separation process.

Geldart’s powder classification scheme is used to classify particles according to size and density, as shown in Fig. 1. There are four main areas. As per Fig. 1, zirconia, bronze and steel represent A, B and D groups, respectively.

The zirconia particles are small (70 µm) and have a relatively low density (3830 kg/m³). Aerated particles should fluidize easily without forming bubbles at low gas velocities. In this area, significant bed expansion can be expected before bubble formation starts [2]. Even though shows that the zirconia particles are on the borderline between group A and B zirconia has been considered as group A particles due to the quick bubbling formation under low velocities observed during fluidization. Luis et al. have found the minimum fluidized velocity for zirconia particles as 0.024 m/s by using zirconia particles with 30 µm particle size and 5890 kg/m³ primary particle density while investigating particle agglomeration conditions [3].

Fig. 1. Geldart’s particle classification diagram (particle size vs particle density) [2]

The bronze particles have the characteristics of group B, “sand-like” or “bubbly” particles. Here, excess bubbles will
appear when the minimum fluidization velocity is exceeded, and the bubbles can grow to large sizes in this regime [4].

The steel particles are comparatively large and dense. Fig. 1 indicates that the steel particles are on the borderline between group B and D, but they can be considered belonging to group D due to the behavior observed during fluidization. When the velocity is increased, jets can form in the bed, and materials can be blown off with the jet in a spouting motion. Such particles may be difficult to fluidize in deep beds. Bubbles coalesce and grow in size rapidly, and severe channeling can be observed if the fluidization gas is not well distributed [4].

There has been a study done by O. Molerus to interpret all the Geldart group particles by considering cohesion forces which is a governing factor for the minimum fluidization velocity [5]. Apart from that several studies have been conducted to investigate the minimum fluidization behavior of different particles (with different particle sizes and densities) experimentally and numerically which represent different groups in Geldart diagram [1], [6], [7]. This study basically focuses on how will the experimental and CFD modelling of the minimum fluidization of particles of group A, B, and D in Geldart diagram can be differed.

The particle regimes were selected based on the observations during the fluidizations and the mean particle size \(X_{50}\) of the particles even though particle samples represented a range of particles sizes.

### III. EXPERIMENT SETUP AND PROCEDURE

An in-house built lab-scale fluidized bed (see Fig. 2 and Fig. 3) was used to measure the minimum fluidization velocity of pure zirconia, steel, and bronze under a uniform airflow. The bed is cylindrical with a height of 1.4 m and a diameter of 0.084 m and is made out of Lexan plastic. There are pressure sensors placed along the bed with a 10 cm distance between them. Sierra mass flow controllers are used to adjust the airflow by means of a pressure reduction valve. A LabVIEW® program is installed on a PC to log the data via a controller unit.

The bed material was added manually from the top of the cylinder. Then the air flow rate was gradually increased until the slugging regime was reached. The air flow rate and pressure values were logged at regular intervals. This procedure was followed for all particle types.

A summary of parameters related to the experiment are shown in Table I. The particle size distribution was measured using a laser diffraction instrument by considering the projected volume of the particles.

### IV. COMPUTATIONAL SCHEME AND MODEL

The continuity equation and momentum equation for the gas phase without reactions and interface mass transfer are given by Eq (1) and (2), respectively [9], [10]. Here \(F\) is the volumetric momentum exchange rate between gas and particles.

\[
\frac{\partial \theta \rho_f}{\partial t} + \nabla \cdot (\theta_f \rho_f \mathbf{u}_f) = 0 \tag{1}
\]

\[
\frac{\partial \mathbf{u}_f}{\partial t} + \nabla \cdot (\theta_f \rho_f \mathbf{u}_f^2) = -\nabla p + \nabla (\theta_f \tau_f) + \theta_f \rho_f g - F \tag{2}
\]

The rate of momentum transfer between fluid and solid phases per unit volume is given by Eq (3) where \(f(x, u_p, p, V_p, t)\) is the particle probability function.

\[
F = \iiint f V_p \rho_p \left[ \mathcal{D} (u_p - \mathbf{u}) - \frac{1}{\rho_p} \nabla p \right] dV_p \cdot d\rho_p \cdot du_p \tag{3}
\]

The time evolution of \(f\) can be obtained by the Liouville equation as given in Eq (4) for the particle distribution function.

\[
\frac{\partial f}{\partial t} + \mathbf{u} \cdot \nabla f = 0 \tag{4}
\]
The particle acceleration balance \( A \) is given in Eq (5). In CPFD software Barracuda, particle interactions are modelled by using an efficient particle stress function. Hence, the particle normal stress \( \tau \) is given by Eq (6) [9], [11] where \( P_s \) is a constant with the units of pressure and \( \beta \) is a constant with a recommended value between 2 and 5 while \( \epsilon \) is a very small number depends on the application.

\[
A = D(u_f - u_p) - \frac{1}{\rho_p} \nabla p + g - \frac{1}{\rho_p \rho_f} \nabla \tau
\]

\[
\tau = \frac{10 \rho_f \rho_p^\beta \theta_p}{\max \{ \theta_{cp} - \theta_p (1 - \theta_p) \}}
\]

The commercial computational particle fluid dynamics (CPFD) software Barracuda was used to simulate the system using available drag models. The Wen-Yu and Wen-Yu-Ergun fluidization drag models gave the best results [12] [13]. A brief description of the Wen-Yu drag model is given below.

The fluid drag on a particle is given by Eq (7) and the drag function \( D \) in the Eq (7) is given by the Eq (8).

\[
F_p = m_p D(u_f - u_p)
\]

\[
D = \frac{3}{8} C_d \rho_f(u_f - u_p)
\]

The drag coefficient \( C_d \) is a function of Reynolds number \( (Re) \) and the fluid volume fraction \( (\theta_f) \), as seen in Eq (9)-(11)

\[
C_d = \frac{24}{Re} \theta_f^n 0 \leq Re \leq 0.5
\]

\[
0.5 \leq Re \leq 1000
\]

\[
1000 < Re
\]

The Wen-Yu-Ergun drag model is a combination of the Wen-Yu and Ergun drag models. In this combined model, the drag function \( D \) in Eq (7) is defined as follows:

\[
D = D_1 \quad \theta_p < 0.75 \theta_{cp}
\]

\[
D = D_2 \quad \theta_p > 0.85 \theta_{cp}
\]

Here, \( D_1 \) is equal to the \( D \) function defined in Eq (8), and \( D_2 \) is defined in Eq (15).

\[
D_2 = 0.5 \left( \frac{c_1 \theta_p}{\theta_f \theta_{cp} + c_2} \right) \rho_f \left( u_f - u_p \right)
\]

The default values used in CPFD software Barracuda for the coefficients in the Wen-Yu model and Wen-Yu-Ergun model are given in TABLE I. [14]
The experimentally determined minimum fluidization velocities and the simulated values were approximately the same for bronze and steel particles, but not for the zirconia particles. Drag model coefficients are usually determined based on data fitting of experimental data generated by fluidization of different particle types. The coefficients used in Barracuda may be not optimized for particles laying on the boundary between the A and B areas in Geldart classification chart (see Fig. 1). Furthermore, agglomeration of particles into clusters of particles can lead the particles to be effectively bigger particles and hence higher fluidization velocities can be expected during the experiment [15].

Another contribution to the discrepancy could be that the particle size distribution was not exactly the same in the computational model as in the experiments. Accurately specifying the PSD in Barracuda is important for correct prediction of the minimum fluidization velocity and the bed pressure drop, especially for smaller particles.

In Fig. 9-Fig. 11 snapshots from the simulation of zirconia, bronze and steel particles, respectively, are shown as a function of increasing air velocities. The zirconia particles get fluidized at 0.008 m/s, which is a low value compared to the bronze and steel fluidization velocities. In Fig. 10, it can be clearly seen that there is a significant bed expansion just before bubbling starts around 0.013 m/s. The bed expansion was observed during the experiments as well. These are clear characteristics of group A behavior, which justifies the classification of zirconia particles as belonging to group A. Fluidization of bronze particles was observed at 0.08 m/s in the simulations as shown in Fig. 9. Excessive bubble formation is observed at velocities higher than the minimum fluidization velocity, and bubbles grow rapidly with increased velocities. These phenomena, which are among the core characteristics of group B particles, were observed in the experiments as well.

The steel particles are fluidized at a velocity between 0.22 and 0.25 m/s. Above 0.25 m/s, bubbling starts. Steel particles are considered as group D particles, which are likely to generate large consolidated bubbles, and above a velocity of 0.25 m/s, bubbles do consolidate and generate larger bubbles. This behavior was observed during the experiments and can also be seen in Fig. 11 at 0.3 m/s. This justifies the classification of steel particles as being group D particles.
VI. CONCLUSION

The experimentally determined minimum fluidization velocities for zirconia, bronze, and steel were found to be 0.015, 0.07 and 0.27 m/s, respectively. The corresponding values from the Barracuda simulations were 0.008, 0.08 and 0.23 m/s. The Wen-Yu and Wen-Yu-Ergun drag models gave the best results compared to the other drag models available in CPFD software Barracuda.

The investigated zirconia, bronze and steel particles can be classified as Geldart A, B, and D particles, respectively. This classification fits with experimental data as well as the Geldart diagram.

The CFD predictions for Geldart B and D particles corresponded well with the experimental data. However, the simulated results for the A particles need further investigation, as these were not in line with the experimental results.

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