

USE OF THE CFD TOOL TO CHECK FLUID DYNAMIC BEHAVIOR OF A FLUIDIZED BED WITH DIFFERENT GEOMETRIC CHARACTERISTICS

USO DA FERRAMENTA CFD PARA VERIFICAR O COMPORTAMENTO FLUIDODINÂMICO DE UM LEITO FLUIDIZADO COM DIFERENTES CARACTERÍSTICAS GEOMÉTRICAS

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Abstract

Fluidized beds are widely used in industrial processes and computer simulation has been growing in use and its planning. This research aimed to comparing the minimum fluidization velocity between two beds besides getting the knowledge of the characteristics of the system, enabling the contribution to the reduction of costs involved in the process and its optimization. The 3D beds were constructed with dimensions 1 m x 0.2 m ranging in thickness from 0.012 m to 0.1 m using mesh of 0.01 m for the reactor body and a refining to 0.005 m at the inlet. Glass beads were used as solid stage and air as transport fluid. It was possible to verify the flow development through the bed, from the fixed bed state to the turbulent flow and the minimum fluidization velocity obtained was 0.06 m/s and 0.07 m/s for the first and second bed, respectively. The obtained values are close to those found in literature, indicating that the mesh used in the study was adequate to the equipment and to the computational time available to obtain the data. This predictive data is of paramount importance for the planning and design of real bed construction, serving the basis for this.

Keywords: Fluidization, CFD, Porosity, Simulation, Computational simulation.

Resumo

Leitos fluidizados são amplamente utilizados em processos industriais, e a simulação computacional vem ganhando espaço no seu planejamento. Esta pesquisa objetivou estudar o escoamento no interior de dois leitos fluidizados e se justifica pôr o conhecimento das características do sistema poder contribuir com a diminuição dos custos envolvidos no processo, bem como possibilitar sua otimização. Os leitos 3D foram construídos com as dimensões 1m x 0,2m variando a espessura de 0,012 m e 0,1 m, utilizando malha de *mesh* 0,01 para o corpo do reator e um refino para 0,005 *mesh* na entrada. Utilizou-

se esferas de vidro como parte sólida e ar como fluido de transporte. Foi possível verificar o desenvolvimento do escoamento através do leito, passando do estado de leito fixo até o fluxo turbulento e a velocidade de mínima fluidização obtida foi de 0,06 m/s e 0,07 m/s para o primeiro e segundo leito, respectivamente. Representando resultado próximo aos encontrados na literatura com tempo computacional satisfatório demonstrado pelos gráficos de porosidade que demonstram de forma visual o padrão de dispersão das partículas no interior do sistema. Esses dados preditivos são de suma importância para o planejamento e projeto de construção de leitos reais, servindo de base para tal.

Palavras-Chaves: Fluidização, CFD, Porosidade, Simulação, Simulação Computacional.

1. Introduction

Fluidized beds are widely used in various industrial applications including particle drying, solids coating and granulation, catalytic synthesis and reactions, catalytic regeneration, combustion and coal gasification [4], due to its excellent mixing and heat transfer, and interfacial mass properties. [14].

In order to achieve the desired product and to safely improve the efficiency is necessary to choose a suitable model for gas-solid bed contact. Normally in fluidization, the action of a gas increases gradually the solid particles velocity, above the minimum fluidization, where there is a gradual suspension of the solid material which happens until the imminent drag. Between minimal fluidization and the drag of the particles there may be three generic regimes, bubbling fluidization, piston fluidization and turbulent fluidization. Depending on the particle, bubbling fluidization can be observed just after the minimum fluidization velocity, which bubble formation occurs in the distributor boundaries [9]. The size of the bubbles and their propagation along the column depends on the characteristics of the particle involved. Turbulent fluidization starts when the gas velocity is greater than the particle terminal velocity, at this moment the pressure oscillations along the bed decrease due to the large bubbles and the remaining voids from the piston regime, becoming more unstable, often disappearing. The next phase is called pneumatic conveying and it happens when the solid particles begin to follow the fluid phase and are dragged out of the column, making the bed diluted [11].

The Computational Fluid Dynamic (CFD) has been proved to be a valuable and useful method to explore the complicated fluid dynamics in the fluidized bed. CFD softwares uses numerical models, that for fluid-particle flows can be classified according to the behavior of the particulate and fluid phases: these methods are Eulerian-Eulerian and Eulerian-Lagrangian [13].

In the Eulerian-Eulerian method, the two phases are involved as a continuous interpenetrated, which both phases are described by a set of conservation equations that have terms in the form of interaction. In the Eulerian-Lagrangian model the fluid phase behave like a continuous phase, where mass, momentum and energy conservation equations are solved for this phase, while the solid phase is analysed as a discrete phase, tracking each individual particle by integration of all forces acting on it and interaction forces between particles [1]. These last method requires high computational capacity for particle tracking, and because of this limitation it is applied in small or medium scale problems [8].

However, a major challenge encountered was the acquirement of experimental data with a good degree of detail, and this difficulty is even more noticeable for three-dimensional systems, especially in large-scale cases, this is due to the difficulty of implementing instrumentation devices and the high computational effort required for this procedure. Due to these obstacles large-scale computational simulations of fluidized beds occur in two-dimensional (2D or pseudo-2D) systems. But with technological evolution, the availability of computational power and more efficient numerical methods has grown, so 3D fluidized bed simulations become more feasible [15].

The research developed in this work aimed to study, through CFD simulations, the flow inside a 3D fluidized bed of a gas-solid system and, from the obtained data, generate the characteristic curves of the bed, discuss the porosity profiles and analyze the particular characteristics for a specific particle and bed conformation.

2. Materials and Methods

The 3D CFD for the fluidized bed was analysed in two different sizes, the first with the dimensions 1m x 0.2 m x 0.1 m with 30797 nodes and 26928 elements and the second varying the thickness to 0.012 m with 15327 nodes and 9880 elements, both, mesh 0.01 m for the reactor body and a refining for 0.005 m at the input. These geometries are shown in Fig. 1.

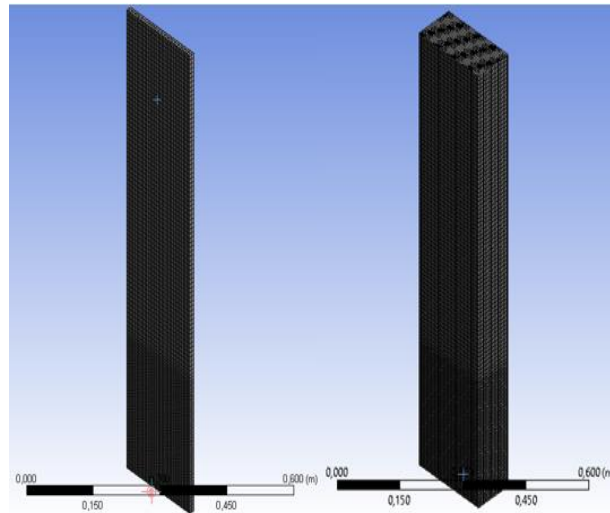


Figure 1: Mesh settings applied to geometry

The material used as a fixed phase in the simulation was glass spheres with 160 and 125 μm in diameter, respectively in systems 1 and 2, sphericity 1 and density of 2500 Kg/m^3 . The transport fluid was air. Defluidization was performed from 0.20 m/s to 0.02 m/s velocities. The conditions and models used in this system are shown in the Table 1.

The simulation was performed in Ansys Fluent 2019R2™, on a computer with the following technical characteristics: Intel® Core™ i5-5200U CPU @ 2.20GHz with 4 cores, 8 GB RAM DDR3 1600MHz and Windows 10 Professional 64-bit system.

Table 1: Parameters adopted in processing operations

Process Parameters	
Model	Euleriano Multiphase: (Implicit)
Fluid – Particle Interaction	Syamlal-Obrien
Kinetic viscosity	Syamlal-Obrien
Granular Viscosity	Lun-et-al
Solids Pressure	Syamlal-Obrien
Radial distribution	Lun-et-al
Bed Filling Height	0.2 <i>m</i>
Volume fraction of solids	0.6
Convergence Criterion	10^{-3}
Time Step Size	10^{-3} <i>s</i>
Maximum Iteration/Time Step	200
Relaxation Parameters	Pressure – 0.2 <i>Pa</i> Density – 1 <i>Kg/m³</i> Body forces – 1 Granular Temperature – 0.2 Volumetric Fraction – 0.2 Momentum – 0.2 <i>n . m</i>

3. Theory and calculation

The momentum exchange between phases, presented on Eq. 1, is based on the fluid-solid exchange coefficient K_{fs} Solidum momentum conservation s [5].

$$\frac{\partial}{\partial t}(\alpha_s \rho_s v_s) + \nabla(\alpha_s \rho_s v_s v_s) = -\alpha_s \nabla p - \nabla p_s + \nabla \tau_s + \alpha_s p_s g + \alpha_s p_s (F_s + F_{l,s} + F_{vm,s}) + \sum_{f=1}^N k_{fs} (v_f - v_s) + m_{fs} v_{fs} \quad (1)$$

The fluid-solid exchange coefficient K_{fs} can be written in the following general form Eq. 2, [5]:

$$K_{fs} = \frac{\alpha_s \rho_s f}{\tau_s} \quad (2)$$

Particle Relaxation Time (Eq. 3) [5]:

$$\tau_s = \frac{\rho_s d_s^2}{18 \mu_f} \quad (3)$$

For [5] Model (Eq. 4):

$$f = \frac{C_D Re_s \alpha_f}{24 v_{r,s}^2} \quad (4)$$

This model is based on terminal velocity measurements of fluidized bed particles. Dalla Valle (1948) derived drag function (Eq. 5), this equation is modified This equation that is [5] from was created after the of [10] :

$$C_D = \left(0.63 + \frac{4.8}{\sqrt{\frac{Re_s}{v_{r,s}}}} \right)^2 \quad (5)$$

Fluid-solid exchange coefficient has the form (Eq. 6) [5]:

$$k_{fs} = \frac{3 \alpha_s \alpha_f \rho_f}{4 v_{r,s}^2 d_s} C_D \left(\frac{Re_s}{v_{r,s}} \right) |v_s - v_f| \quad (6)$$

Where $v_{r,s}$, is the terminal velocity for the solid phase (Eq. 7) [5]:

$$v_{r,s} = 0.5(A - 0.06 Re_s + \sqrt{(0.06 Re_s)^2 + 0.12 Re_s (2B - A) + A^2}) \quad (7)$$

Where A is (Eq. 8):

$$A = \alpha_f^{4.14} \quad (8)$$

To $\alpha_f \leq 0.85$ (Eq. 9):

$$B = 0.8 \alpha_f^{1.28} \quad (9)$$

To $\alpha_f \geq 0.85$ (Eq. 10):

$$B = \alpha_f^{2.65} \quad (10)$$

The simulation was performed by implementing the data into the software and from there the air intake was varied until the desired characteristics for the bed were obtained.

The graphs and comparatives (porosity and velocity profiles) were made from the capture of bed frames at certain points or velocities.

Finally, it is important to emphasize that the reason for making the change in particle sizing and diameter is to demonstrate how small changes in variables can influence the results obtained.

4. Results and Discussions

The results analysis was performed through the graphs of porosity profiles, pressure drop and bed characteristic curve. Each physical minute of simulation took an average of two and a half hours to complete the iterations, at the end of the study, 80 hours of computer simulation. The results are in Fig. 2 for bed whit dimensions 1 m x 0.2 m x 0.1 m:

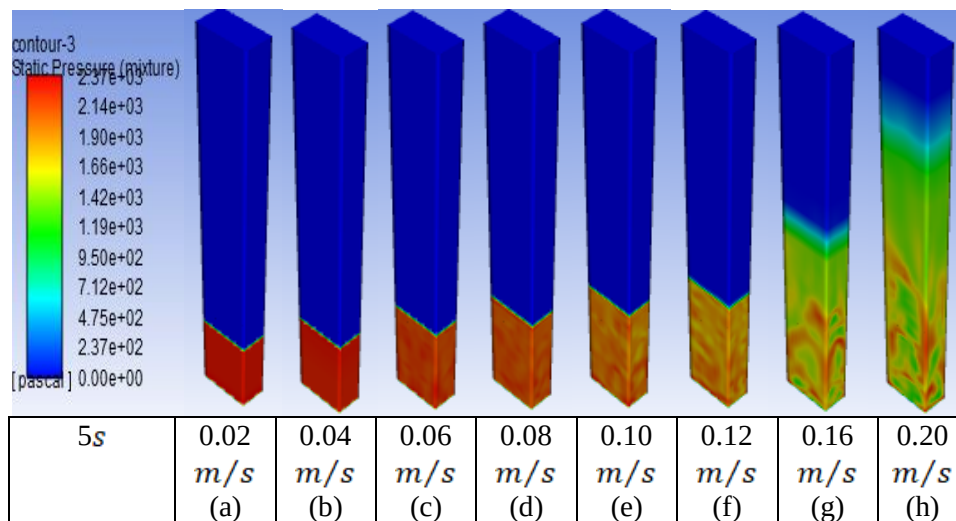


Figure 2: 5 s time bed porosity profiles for different air flow rates for 1 m x 0.2 m x 0.1 m dimension.

When the fluid ascends to the particle bed with a velocity unable to cause it to move, Fig. 2 (a), at this moment the fluid percolates the spaces between the static particles. As the velocity of the incoming gas increases, a small movement and expansion of the particles in the bed begins to be observed. As this gas flow is increased, the forces acting on the bed (drag, thrust and weight) tend to equal, and the particles begin to offer lower fluidization resistance acquiring fluid characteristics. At this point, we have the fluidized bed Fig. 2 (b, c, d, e, f), where there are favorable conditions for heat and mass transfer, indispensable for the various operations for which the bed is indicated, the pressure drop from that moment remains constant. Increments in gas flow above the minimum fluidization velocity result in a progressive expansion of the particles towards the top of the bed, generating turbulent, formation of bubbles and preferential channels of passage, thus having the bubbling bed Fig. 2 (g e h). If the flow increments persists pneumatic transpor is achieved, which is not the desired in this system.

For the second system, Fig. 3 shows the bed porosity profile.

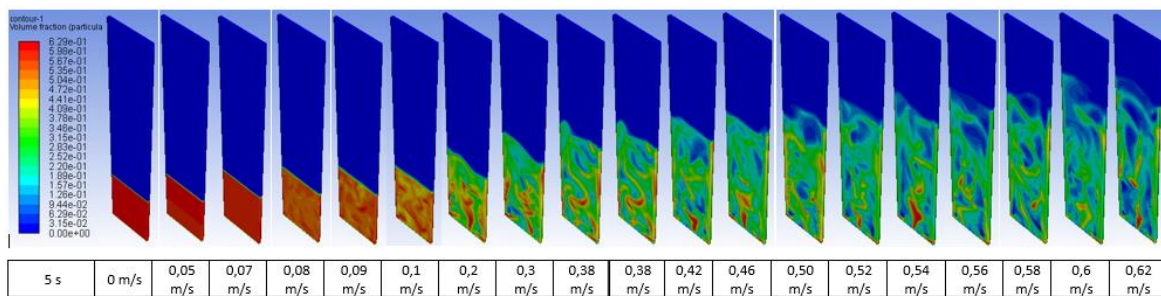


Figure 3: Bed porosity profile based on air inlet velocity variation at time 5 s. dimensions of 1 m x 0.2 m x 0.012 m.

From the velocities 0 to 0.05 m/s the bed goes from fixed to expanded, from this moment 0.07 to 0.1 m/s it is possible to verify the fluidization. The turbulent phase begins at 0.30 to 0.38 m/s, reaching the end at 0.42 to 0.62 m/s demonstrating a chaotic particle flow inside the reactor. From this moment on, increasing velocities, will reach the point of turbulent bed and pneumatic transport, where the particles would exceed the total reactor height [10].

Fig. 4 shows the pressure drop graphs representing the systems based on the air intake pressure in the first and the maximum system pressure in the second.

Both situations were obtained by CFD simulation. From them it is possible to verify the characteristic curve of fluidization, which in the first system happens around the region of the 0.06 m/s velocity, while in the second it is close to the 0.07 m/s velocity. For the first system, the behavior was consistent with those found by Caicedo et. al. (2002) [3], that studied the same type of system, changing glass beds and size ranges. In the present study this variable was presented in only one size for each system, a small variation in the data is expected. Nevertheless, similar values were presented between the systems studied and in comparison with Caicedo et. al. (2002) [3] work, the first system presents similarity, where the minimum fluidization velocity is close to 0.05 m/s for the systems. However, the particle size presented in the second system is not present in the comparative case, and it cannot be used to estimate the minimum fluidization conditions.

The plots in Fig. 4. refer to pressure drop data obtained from the Average Area (Area), Air Intake (Inlet), Interior Reactor (Interior), and Average Volume (Volume). The first three were obtained through surface integrals and the last, volume integral. The behavior of the plots corroborate to what has already been said that the pressure variation tends to increase with increasing velocity.

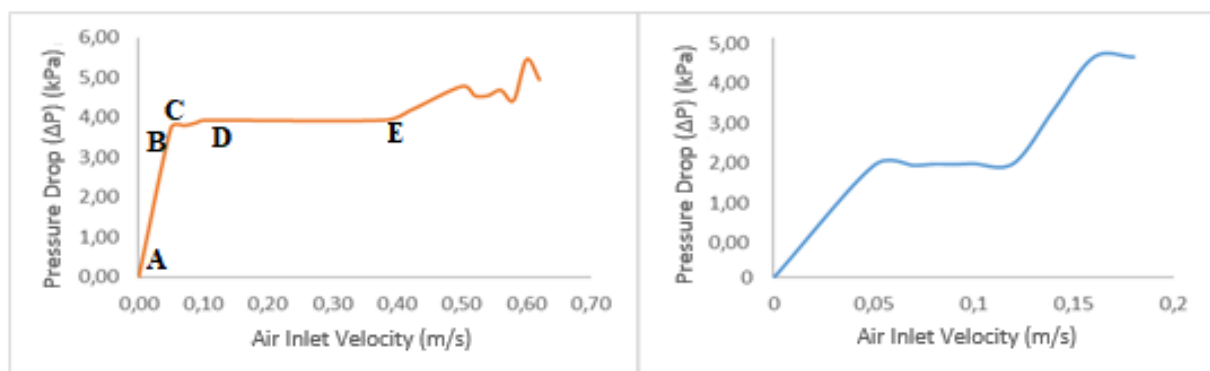


Figure 4: Pressure drop versus air inlet velocity graphs for both systems. The left the thinnest.

The plots in Fig. 4. refer to pressure drop data obtained from the Average Area (Area), Air Intake (Inlet), Interior Reactor (Interior), and Average Volume (Volume). The first three were obtained through surface integrals and the last, volume integral. The behavior of the plots corroborate to what has already been said that the pressure variation tends to increase with increasing velocity.

Comparing the results of this simulation with literature [2] Fig. 4 shows the similarity. The region comprised by the AB interval can be defined as a fixed bed, the particles in this region are well accommodated and the regime is almost always laminar. At point B the pressure drop is equal to the weight of the solids, at this point the bed is almost at rest containing fluid characteristics and it is possible to observe the flow of the bed, and in this sector the particles change position and rearrange themselves. At point C there is a minimal fluidization. In the interval comprised by the CD curve, it indicates the disordered movement of the particles with frequent collisions due to the increased porosity and lower pressure variation along with the increased velocity. In the range matched by AD curve, the bed is said to expand. At point D the pressure drop begins to become constant and no contact between the particles occurs. In the interval DE the velocity varies linearly with the pressure drop until reaching the point E, in this interval the fluidization occurs. At point E the particles begin to be dragged by the fluid and the functionality of the system is lost, in this region the fluidization is named as dilute stage. These characteristics are present in both curves even if the study would be performed with particles of different diameter [2]. The main difference between the characteristic curves is the pressure level where the fluidization occurs. In them is possible to verify that the fluidization occurs at approximately at 4 KPa in the first system and in the second at 2 KPa. Both curves were placed together in Fig. 5.

Due to the difference in particle size and bed thickness, the results obtained may refer to reality, because a higher pressure is required to fluidize a larger particle bed as well as a thicker one [3].

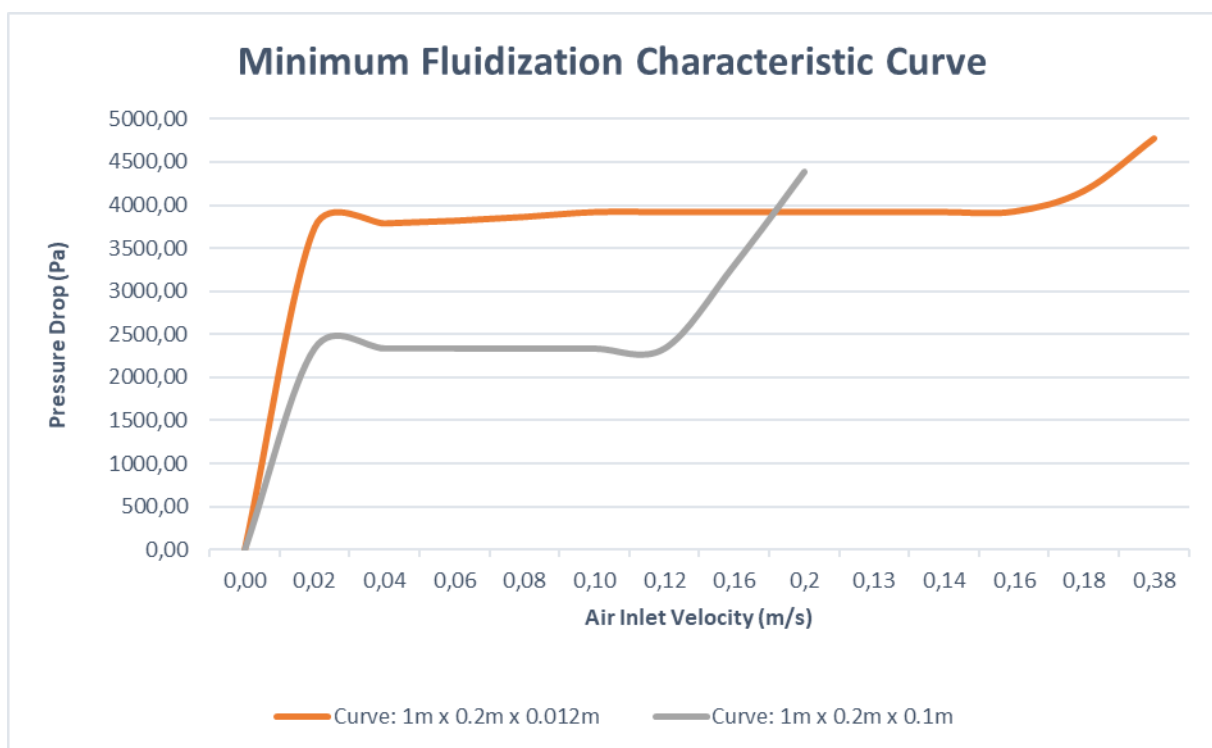


Figure 5: Bed porosity profile based on air inlet velocity variation at time 5 s. dimensions of 1 m x 0.2 m x 0.012 m.

The bed characteristic curve is an experimental method used to determine the minimum fluidization velocity, that matches with the pressure from the air inlet. From the Fig. 5, the minimum fluidization velocities is 0.06 m/s for the 0.012 m thickness curve and 0.07m/s for the 0.1 m thickness curve against a minimum fluidization pressure drop between 2 KPa and 4 KPa, these values were obtained by intersecting the fixed bed line with the horizontal line corresponding to the fluidization region of the material.

The pressure drop versus velocity graph is widely used as an indication of fluidization quality, especially when visual observation is not possible [5].

The minimum fluidization velocity is specific for a particular bed conformation, particularities such as bed height and particle dimensions directly influence this velocity, which makes each system unique for a given characteristic [6].

5. Conclusion

The simulation performed in the present work allowed to infer the minimum fluidization velocity of 0.06 m/s and 0.07 m/s against a minimum fluidization pressure drop of 2 KPa and 4 KPa, for the gas-solid systems (air-glass beads).

Porosity profiles allowed us to identify the various stages of the fluidization process and to infer the rate at which the bed fluidizes, coinciding with the experimental method of the characteristic curve.

Obtained values are close to those found in literature, indicating that the mesh used in the study was adequate to the equipment and to the computational time available to obtain the data.

These predictive data are crucial for the economic feasibility of building real systems and of paramount importance of bed design and construction, as they indicate the appropriated operation parameters and conditions through specific conformations before their physical implementation.

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7. References

- [1] Borges, L. P.; Béttega, R., “Simulação do Comportamento Hidrodinâmico de um Leito de Jorro : Comparação entre Método dos Elementos Discretos (DEM) e Modelo de Dois Fluidos (TFM)”. *Congresso Brasileiro de Engenharia Química em Iniciação Científica*. Anais...Uberlândia (2019). Available inISSN 2359-1757. DOI: [10.5151/cobecic2019-FTSP3](https://doi.org/10.5151/cobecic2019-FTSP3).
- [2] Borges, P. W. S., “*Readequação da Prática de Laboratório de Engenharia Química 1: Leito Fluidizado*”. Graduation Work. Faculdade de Engenharia Química. Universidade Federal de Uberlândia – UFU, Uberlândia (2017). Available in: <https://repositorio.ufu.br/handle/123456789/20874>
- [3] Caicedo, G. R., Ruiz, M. G., Marqués, J. J. P., Soler, J. G., Minimum fluidization velocities for gas-solid 2D beds. *Journal Chemical Engineering and Processing*, v. 41, p. 761–764, (2002). DOI: [https://doi.org/10.1016/S0255-2701\(02\)00005-3](https://doi.org/10.1016/S0255-2701(02)00005-3)
- [4] Cremasco, M. A., “*Operações Unitárias em Sistemas Particulados e Fluidomecânicos*”. São Paulo: Blucher, v. 212, p. 423, (2012). ISBN: 9788521205937
- [5] Daleffe, R. V.; Freire, J. T. *Analysis of the fluid-dynamic behavior of fluidized and vibrofluidized bed containing glycerol*. *Brazilian Journal of Chemical Engineering*, v. 21, n. 1, p. 35–46, 2004. DOI: <https://dx.doi.org/10.1590/S0104-66322004000100005>
- [6] Felipe, C., “*Identificação e monitoramento de regime fluidodinâmico em leitos fluidizados gás-sólido*”. Doctoral Thesis .Universidade Estadual de Campinas – UNICAMP, Campinas, (2004) . Available in: <http://repositorio.unicamp.br/jspui/handle/REPOSIP/267692>

- [7] Gera, D., Gautam, M., Tsuji, Y., Kawaguchi, T., & Tanaka, T., *Computer simulation of bubbles in large-particle fluidized beds*. Journal Powder Technology, v. 98, n. 1, p. 38–47, (1988). DOI: [https://doi.org/10.1016/S0032-5910\(98\)00017-5](https://doi.org/10.1016/S0032-5910(98)00017-5)
- [8] Iqbal, N.; Rauh, C.; Delgado, A., *Numerical simulations of particle-laden jet/spout flows using Eulerian-Lagrangian approach*. Journal Procedia Engineering, v. 102, p. 867–876, (2015). DOI: <https://doi.org/10.1016/j.proeng.2015.01.207>
- [9] Kunii, D.; Levenspiel, O., *Fluidization Engineering*. Stoneham, ButterworthHeinemann, v. 3, (1991). ISBN: 0-409-90233-0
- [10] Nitz, M.; Gardani, R., *Fluidização Gás-Sólido – Fundamentos e Avanços*. Journal Revista Brasileira de Engenharia Química, p. 20–24, (2008). Available in: <https://maua.br/files/artigos/artigo-fluidizacao-gas-solido-prof-nitz.pdf>
- [11] Prieto, W. H., “Aplicação da teoria do caos em um leito fluidizado utilizando-se partículas a, b e d da classificação geldar”. Masters Dissertation. Universidade Estadual de Campinas – UNICAMP, Campinas, (2014) . Available in: <http://repositorio.unicamp.br/jspui/handle/REPOSIP/266069>
- [12] Wen, C. Y.; Yu, Y. H., *Mechanics of fluidization*. Chemical Engineering Progress, Symposium Series, v. 62, n. 1, p. 100–111, (1966).
- [13] Wu, K.; De Martín, L.; Mazzei, L.; Coppens, M., *Pattern formation in fluidized beds as a tool for model validation: A two-fluid model based study*. Journal Powder Technology, v. 295, p. 35–42, (2016). DOI: <https://doi.org/10.1016/j.powtec.2016.03.011>
- [14] Wu, K.; De Martín, L.; Coppens, M. O., *Pattern formation in pulsed gas-solid fluidized beds – The role of granular solid mechanics*. Journal Chemical Engineering, v. 329, p. 4–14, (2017). DOI: <https://doi.org/10.1016/j.ces.2017.05.152>
- [15] Yang, L.; Padden, J. T.; Buist, K. A.; Kuiper, J. A. M., *Three-dimensional fluidized beds with rough spheres: Validation of a Two Fluid Model by Magnetic Particle Tracking and discrete particle simulations*. Journal Chemical Engineering Science, v. 174, n. September, p. 238–258, (2017). DOI: <https://doi.org/10.1016/j.ces.2017.09.014>