

COB-2021-1952 ANALYSIS OF THE FLUID DYNAMICS OF SPOUTED BED WITH AND WITHOUT DRAFT TUBE: MODELING AND SIMULATION

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Abstract.

The spouted bed was created in Canada in 1954, to improve the efficiency of grain drying, it was seen that the equipment offers an effective fluid/solid contact and generating an excellent degree of mixing, resulting in high heat and mass transfer rates between phases. This equipment is used in different industrial areas, such as drying, particle coating, mechanical extraction. The conventional spouted bed presents limitations such as the phenomenon known as "short circuit". To minimize this effect an internal tube is used. In this context, the purposed this word is to evaluate the fluid dynamics behavior of the conventional spouted bed and with an internal tube using Computational Fluid Dynamics (CFD). The Eulerian-Eulerian approach was adopted to simulate gas-particle flow in a three-dimensional domain. The constitutive correlations and the turbulence model $k-\epsilon$ were adopted. All simulations were conducted using the commercial package Ansys Fluent®. The results of the simulations show the formation of the spouted bed (with or without draft tube) shows three regions: annular, spouted and fountain. A discrepancy was also seen in the first moments of the formation of the spouted bed. These results ratify the observation of different works reported in the literature. The results also showed a dependence on the behavior of the spouted bed with the flow rate of the gas stream.

Keywords: multiphase flow, Spouted bed, CFD, Eulerian-Eulerian approach.

1. INTRODUCTION

The spouted bed is an equipment developed due to the need for drying wheat grains in Canada in 1955 by Mathur and Gishleer, to increase efficiency and reduce the process time, using higher temperatures, occurs within the bed cyclical movements of particles, with regions with distinct characteristics, such as the angular region, stream region, and source, shown in Figure 1.

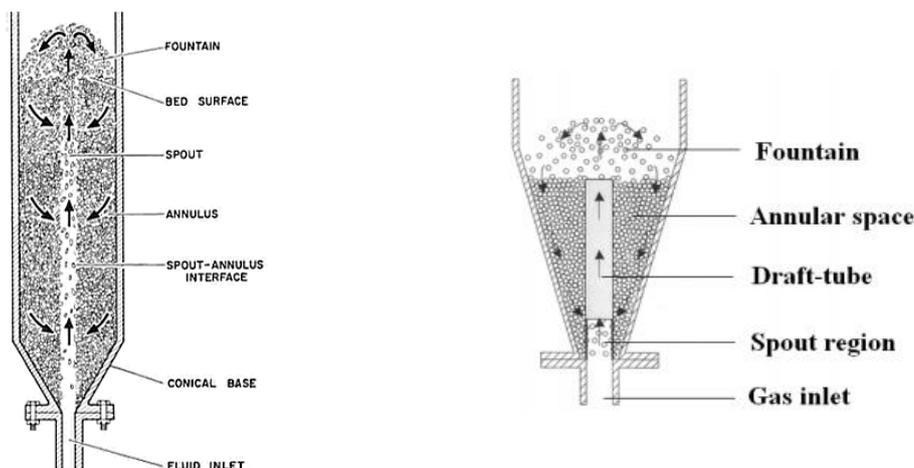


Figure 1. Typical fluid dynamic regions of the spouted bed with and without the draft tube (Mathur, K. B. and Epstein, 1974; H. Altzibar, 2010)

Traditionally, the spouted bed has a cylindrical column and a cone base used to reduce dead spaces at the bottom and increase the movement of solid particles from an inlet cross section. There are three flow regions generated by the gas-solid fluid that seen in Figure 1:

- Central Stream and Spout Annulus Interface: Extends from the bottom of the equipment to near the top, called the Fountain. In this region there is a high velocity of the jet air, rising the solid particles next the jet.
- Fountain and Bed Surface: When the particles rise to the maximum height and suffer a deceleration caused by the gravity, the particle lost kinetic energy and fall on the lateral regions.
- Annulus: with the fall on the upper surface of the angular region, which then descends to the lower region, where it has a high concentration of particles, when they reach the base of the bed, they complete the cyclic movement that is quite defined.

In the border between the annular region and the central stream, occurs the problems of "short-circuits". So, the draft tube is inserted to separate these two regions and supply the ideal cycle of the movement of particles in the bed.

The spouted bed is the most attractive for coating operations (tablets, gelatin capsules, palletization, seed inoculation), given the homogeneity of the coating obtained, when compared with other equipment (Mathur & Epstein, 1974, Duarte, 2006).

Although the spouted bed presents an extensive use, it presents limitations due to its fluid-dynamic behavior, such as the phenomenon called "short-circuit" of the particles, which consists of the return of particles that are in the annular region to the spouted region, therefore prevented from completing the cycle in the equipment. This phenomenon results in a heterogeneous product, due to the longer time of particle residence distribution. So, to eliminate or reduce these effects, Pallai and Németh (1972), Clafin and Fane (1982), suggested the insertion of a central tube (aspiration tube) that channels the air to the spouting region, as illustrated. in Figure 1 the airflow required for the bed to enter the spouting state will be lower.

Understanding the characteristics of the flow in the bed is of great interest for project construction and scale-up. Since this equipment uses multiphase flows, such as gas-solid, the experimental analysis of the particle movement is impaired due to the large amount of it. The observation of the fluid-dynamic behavior and efficiency of the equipment is not ideal with probes, because they alter the flow of the mixture, since the particulate phase is dense and precise measurements of its behavior inside are restricted (Santos, 2008; Viera Neto, 2007).

Multiphase flow is characterized by the presence of a mixture of solid, liquid and gas phases. The mathematical modeling of a spouted bed can follow two different multiphase models said to be Eulerian and Lagrangean. Because of the fluidized nature of the system, Eulerian-Eulerian approach characterized by applying the two-fluid approximation that treats both phases, fluid, and solid, as continuous, and interpenetrating phases as also the volume of one phase cannot be occupied by the others. The mass conservation equations and the Navier-Stokes equations are used to describe the movement of fluid and particles. Depending on the case to be simulated, constitutive equations are used, for example the equations of granular kinetic theory employed for granular flow occurring in systems such as the spouted bed (Bonfim, 2018; Ramos, 2018; Marques, 2013; ANSYS FLUENT THEORY GUIDE, 2015).

Pallai and Németh (1972) apud Mathur and Epstein (1974) analyzed the introduction of the draft tube with the intent of increasing the quality of grain drying. Although the draft tube decreases the heat and mass transfer coefficients, it eases the formation of the stream and avoids the short circuit effect. This effect would cause an increase in the temperature of certain grains, thus obtaining, in the configuration of the equipment without the draft, a more heterogeneous final product. It was also verified a decrease in the range of residence time of the particles, when compared to the conventional bed.

Ramos (2018) analyzed the fluid-dynamic behavior of the spouted bed with the draft tube using computational simulation with the aid of the CFD tool, in a 2D model. With a Eulerian approach by considering the multiphase, gas-solid flow, along with the Granular Kinetic Theory, with the uncertainty of the $k-\epsilon$ dispersive turbulence model. It was concluded that there is a relationship between the bed expansion and the increase in gas velocities, which results in a more developed source region, as it was also saw that the conventional spouted bed demands a longer simulation time to reach the jetting regime compared to the draft tube bed.

Ishikura et al. (2003) studied the fluid dynamics of a spouted bed with a suction tube (a massive, porous suction tube) with a low fraction of fine particles. To analyze the behavior of the as source height, particle recirculation rate of the studied spouted beds, the structure configurations were changed. And it was seen that the minimum jet velocity is proportional with the decrease of the height between the bottom of the draft and the base of the bed and with the decrease of the diameter of the porous draft tube, as well. The minimum jet velocity for the porous draft tube is higher than for the non-porous draft tube. The authors also showed that the solids circulation rate increases with increasing gas velocity.

Santos (2008) presented three proposals for case studies using CFD to simulate them, with one of them the study done with the spouted bed with draft tube, in which their results were validated by experimental data of Vieira Neto (2007), evaluating the effect of the $k-\epsilon$ dispersive turbulence model, exposing the pressure drop and the solids volume fraction profiles for identification of the minimum spouted.

Therefore, the use of computational fluid dynamics supplies detailed information on the fluid-particle interaction in the spouted bed. In this sense, the present work uses the CFD to evaluate the effect of using the draft tube on the spouted bed.

2. METHODOLOGY

The geometric modeling of the spouted bed, illustrated in Figure 2, was created using the ANSYS ICEM® 15.0 tool based on the work of Vieira (2014) and Ramos (2018).

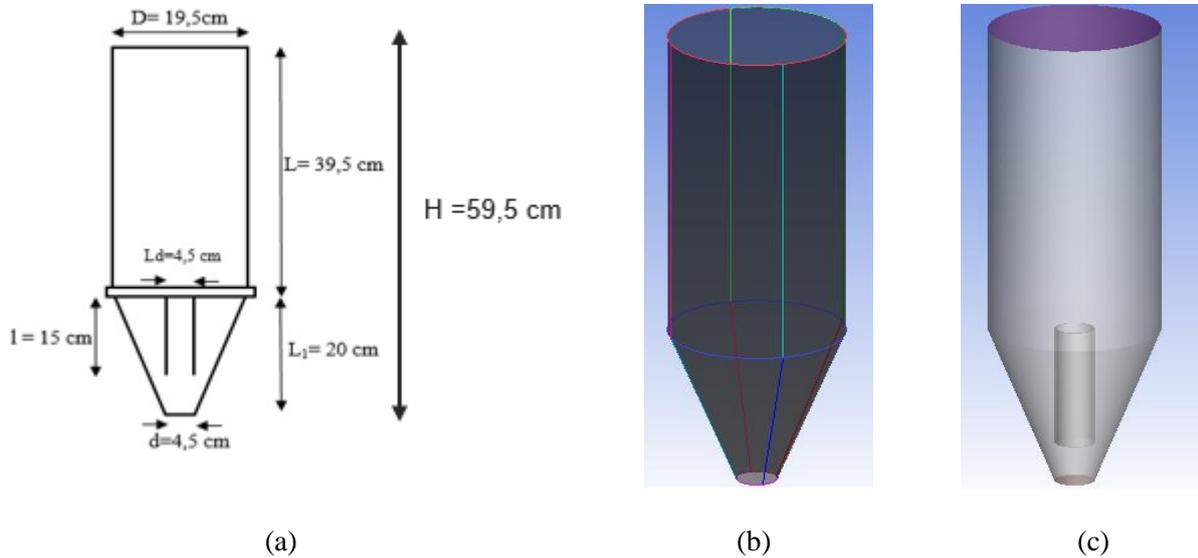


Figure 2: Representation of (a) dimensions (b) geometry of the conventional (c) all draft

The mesh generation followed the recommendations made by Duarte (2006), which says that the mesh refinement should present elements with dimensions between 5 and 10% greater than the average diameter of the particles that form the spouted stream bed. Based on this criterion the mesh of the spouted bed without the draft tube with 24882 elements is shown in the Figure 3a and the spouted bed with the draft tube with 103829 elements (Figure 3b).

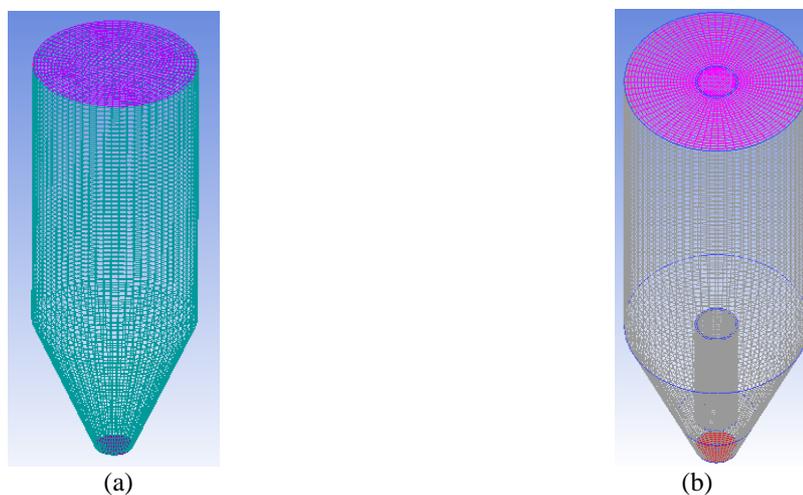


Figure 3. Representation of the spouted bed mesh (a) without (b) with the draft

The mathematical model adopted to obtain the numerical results referring to the fluid dynamic behavior of the spouted bed was based on the equations of conservation of mass and linear momentum, adopting the following considerations:

- Two-phase flow composed of continuous phases.
- The kinetic granular theory was adopted.
- $k-\epsilon$ turbulence model.
- Eulerian-Eulerian approach.
- Newtonian and incompressible fluid.
- Transient regime.
- Interaction forces neglected, except the drag forces.
- Particles are spherical.
- No chemical reaction.

- No mass transfers.

With these considerations the equations of conservation of mass and linear momentum for the gaseous and particulate phases can be written as follows:

(a) Fluid phase
$$\frac{\partial}{\partial t}(\alpha_g \rho_g) + \nabla \cdot (\alpha_g \rho_g \vec{v}_g) = 0 \quad (1)$$

(b) Solid Phase
$$\frac{\partial}{\partial t}(\alpha_s \rho_s) + \nabla \cdot (\alpha_s \rho_s \vec{v}_s) = 0 \quad (2)$$

$$\alpha_g + \alpha_s = 1 \quad (3)$$

ρ - Density, kg.m^{-3}
 α - Volumetric fraction
 v_s, v_g - Particle velocity and gas velocity, m.s^{-1}

(a) Fluid phase
$$\frac{\partial}{\partial t}(\alpha_g \rho_g) + \vec{v}_g \nabla \cdot (\alpha_g \rho_g \vec{v}_g) = -\alpha_g \nabla P + \nabla \cdot \bar{\tau}_g + \alpha_g \rho_g \vec{g} + \beta(\vec{v}_s - \vec{v}_g) \quad (4)$$

(b) Solid Phase
$$\frac{\partial}{\partial t}(\alpha_s \rho_s) + \vec{v}_g \nabla \cdot (\alpha_s \rho_s \vec{v}_s) = -\alpha_g \nabla P - \nabla P_s + \nabla \cdot \bar{\tau}_s + \alpha_s \rho_s \vec{g} + \beta(\vec{v}_g - \vec{v}_s) \quad (5)$$

β - Interface momentum exchange coefficient, $\text{kg.m}^{-3}.\text{s}^{-1}$
 g - Gravity acceleration, m.s^{-2}
 P - Pressure, N.m^{-2}
 $\bar{\tau}_g$ - Reynolds stress tensor for the continuous phase, N.m^{-2}
 $\bar{\tau}_s$ - Solid Tension Tensor, N.m^{-2}

2.1 Initial and boundary conditions

All simulations were performed adopting that the spouted bed was initially with static bed height equal to 0.18 m and porosity is 0.46 and the adopted boundary conditions as illustrated in Figure 4.

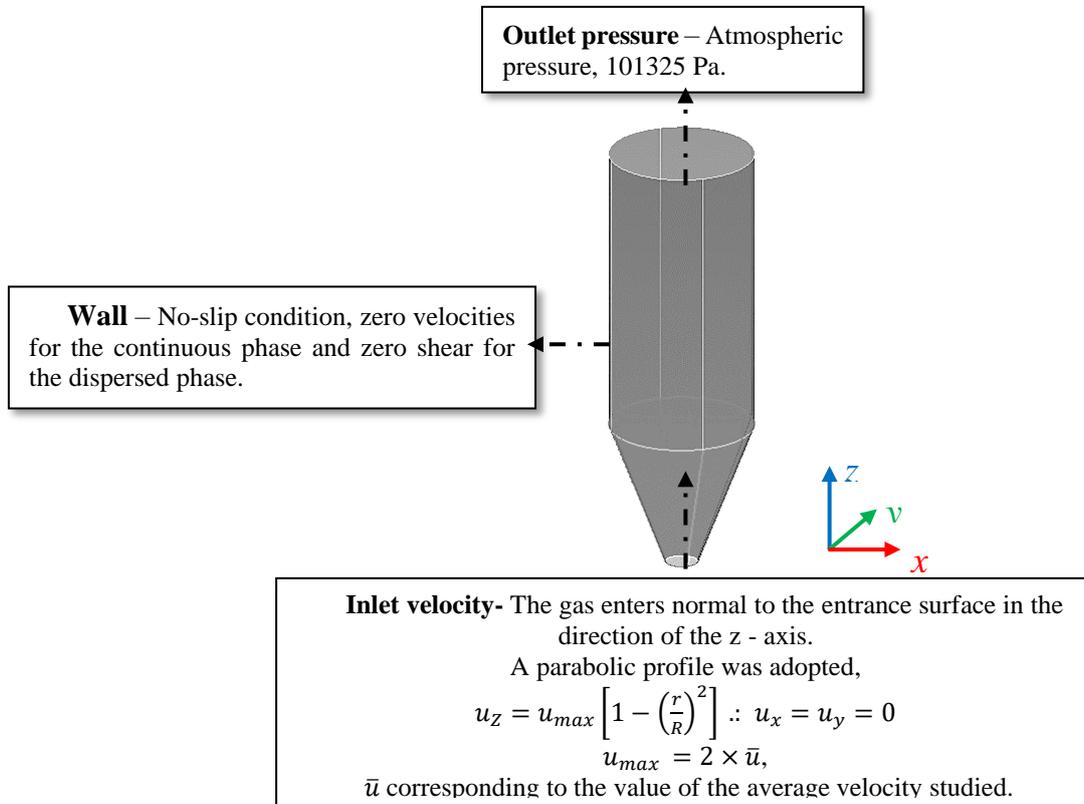


Figure 4. The adopted boundary conditions

The Kinetic Theory of Granular Flow (KTGF) was used to describe the dispersed phase, developed by Lun et al. (1984). The collisions are inelastic between particles, so energy is dissipated and estimated by constitutive equations described for the granular phase. The turbulence model was the standard k- ϵ , based on the works of Ramos (2018) and Santos (2008). The properties of the continuous phase (air) and the dispersed phase (polyethylene) are shown in Table 1-

Table 1. Phase properties.

Property	Air	Polyethylene
Density (kg. m ⁻³)	1,162	906
Viscosity (kg. m ⁻¹ .s)	1,862x10 ⁻⁵	-
Particle diameter (m)	-	0,00308
Volume fraction	-	0,52

General conditions used for numerical simulation of the mathematical models and boundary conditions used for the spouted bed are contained in Table 2.

Table 2. Parameters employed in the numerical simulation.

Item Setup	Parameter	Description/value
Solver	3D	Time step = 1x10 ⁻³ s
	Transient	
	Pressure-based	
Models	Eulerian Multiphase Model	Two phases (air and polyethylene)
	Turbulence Model	K-epsilon (dispersed)
	Drag Model	Syamlal-O'Brien
	Granular Viscosity	Syamlal-O'Brien
	Bulk Viscosity	Lun et al.
	Granular Temperature	Algebraic
	Solids Pressure	Syamlal-O'Brien
	Radial distribution	Syamlal-O'Brien

The convergence criterion set was about 1x10⁻³ and the relaxation factors are in the range of 0.2 to 1.0. A time of 4 seconds was used for reaching the steady state.

3. RESULTS AND DISCUSSIONS

The Figure 5 shows the results of the distribution of the polyethylene volume fraction on the YZ plane at the instant of 1.0 s, considering the gas velocity equal to 8.37 m/s in the inlet. This figure shows the behavior of the spouted beds with and without the draft tube.

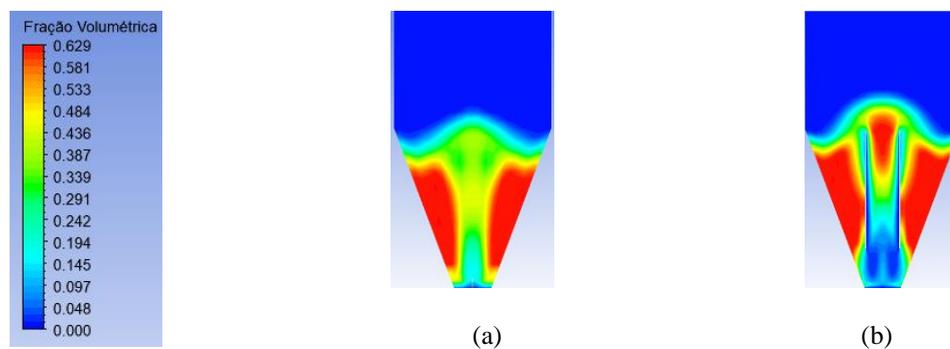


Figure 5. Polyethylene volume fraction profile as a function of time, evaluating the behavior profiles with v_g 8.37m/s (a) without (b) with draft tube.

The volume fraction of polyethylene Figure 5 shows the different regions that make up the spouted bed (annular space, spout and fountain). The annular region showed by reddish regions that have a higher concentration of particles; the

spouted region found in the central region of the bed being showed by the low concentration of particles; and formation of the fountain above the surface of the bed of particles presenting a concentration of solids higher than in the gusher region.

Figure 5 shows that the draft tube directs the gas flow and allows for larger jets, thus showing low pressure drops. This figure shows the formation of fountain region more stable than spouted bed standard stream. The draft tube promotes a more orderly circulation of the solid in the spouted bed. Santos (2008) equally saw this same behavior.

Figure 6 shows the distribution of the volume fraction of polyethylene particles on a YZ plane with 35 cm at different time intervals (0.2, 0.5, 1.0, 1.5 and 2.0 s) for the entrance velocity of the gas stream, 8.73 m/s corresponding to a flow of $40 \text{ m}^3/\text{s}$, for the equipment with and without the draft tube. In both situations it is seen how the three regions tend to form with the evolution of time. The results at the time of 2 seconds show that it was not possible to clearly see the formation of the source region at 1 second, as can be seen in Figure 5b. This fact can be explained by the higher drag forces imposed by the higher velocity. However, at one second, a significant increase in the height of the source region is seen, which was not expected. This fact may be related to the turbulence model used or the empirical correlations of the granular kinetic theory model, which fitted very well considering a two-dimensional domain used by Ramos (2018).

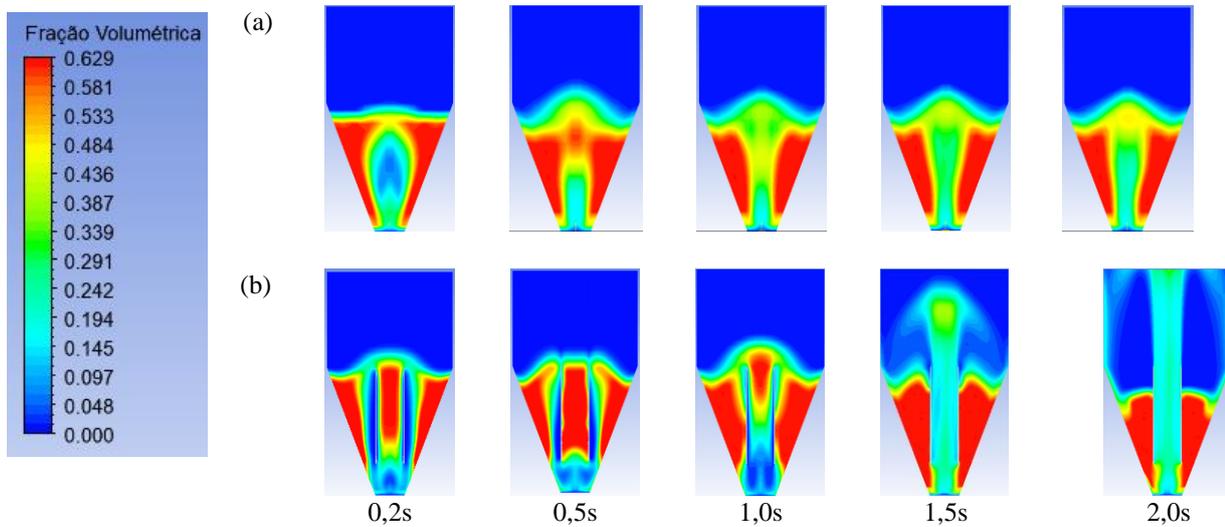


Figure 6. Polyethylene volume fraction profile as a function of time, evaluating the behavior profiles with the air flows at $40 \text{ m}^3/\text{h}$ (a) without (b) with draft tube.

To illustrate the behavior of the particles inside the spouted bed are represented in Figure 7 the velocity vector field of the particles on the YZ plane at the instant 0.7 s , for the entrance velocity equal to 8.73 m/s . Note that the use of equal flow rates does not significantly affect the behavior of the particle bed because of the presence of the draft tube. The vector field shown in Figure 2 shows the descending behavior of the particles. Here the action of gravity induces a weight force greater than the drag forces on the particles due to the injection of gas into the inlet section of the spouted bed.

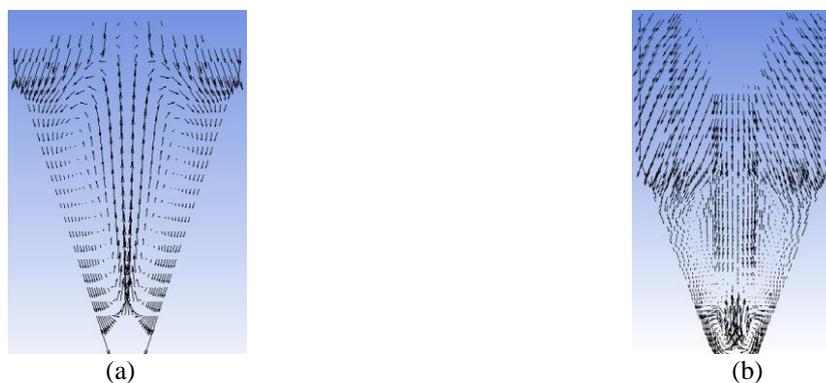


Figure 7: Maps of velocity vectors of particles the time of 0.7 s at 8.73 m/s (a) without (b) with draft tube

In Figure 8 is represented the evolution of the pressure drop between the inlet and outlet sections of the spouted bed as a function of time. In addition to the pressure behavior with time, the volume fraction fields on the YZ plane at different

peak and valley times are represented. The purpose of these representations is to illustrate the behavior of the particles at these instants and how it influences the pressure drop.

Analyzing Figure 8, it is possible to see the behavior of the inlet pressure fluctuations as a function of time. At time $t = 2$ s, the gas stream starts to penetrate the bed of particles providing a displacement of the particles and an expansion of the spouted bed, i.e., the particles change direction and, in some regions, there is an acceleration of the particles and, in other regions, there is a movement in the opposite direction to the stream, due to the action of the weight force is greater than the drag force, returning to the annular region and again exerting pressure at the inlet.

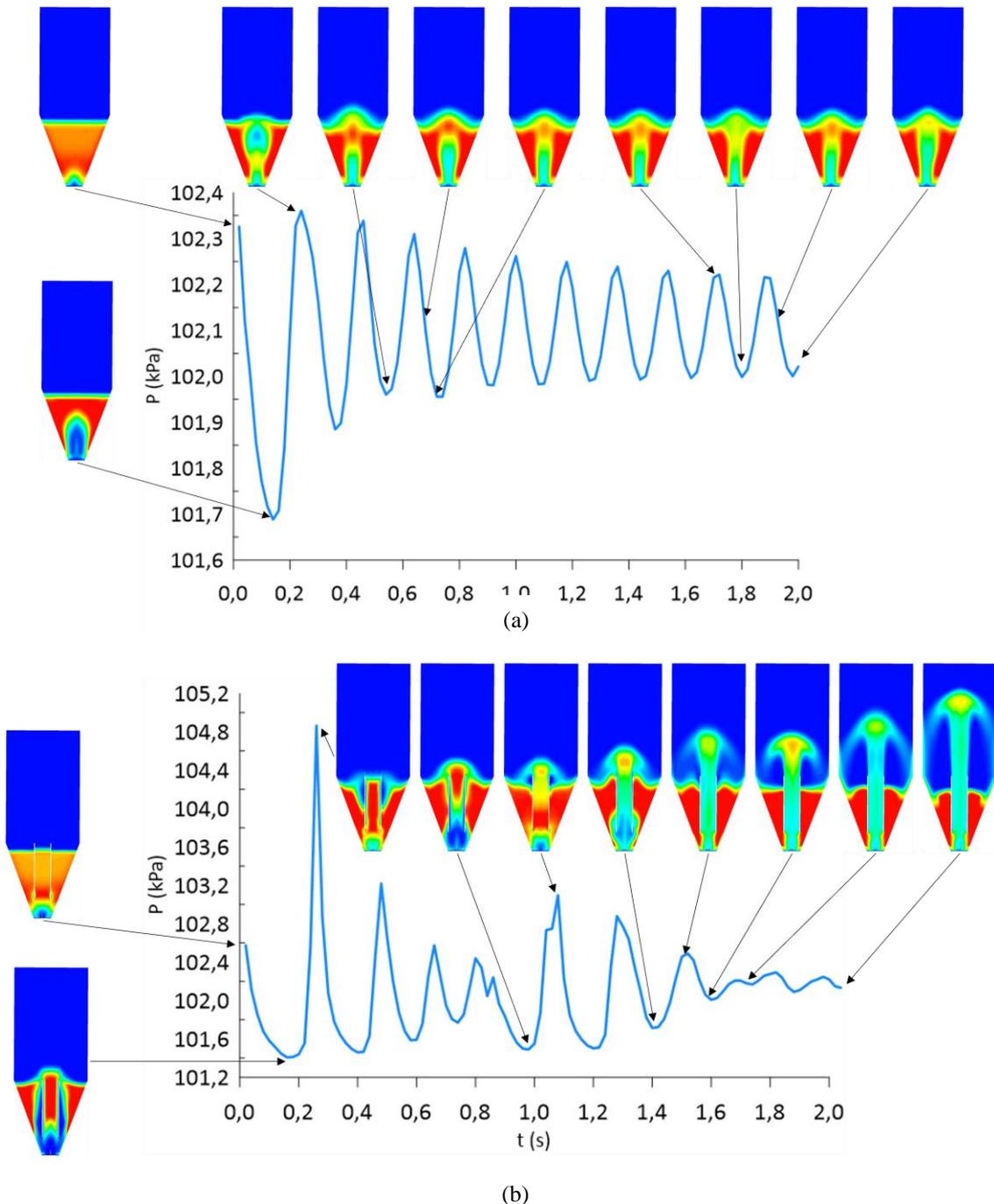


Figure 8: Evolution of the pressure drop in the spouted bed as a function of time at a velocity of 8.73 m/s (a) without (b) with an inner tube

We can see that the behavior of the particles in the spouted bed, Figure 8, is also related with the variation of the bed porosity. The increase in bed porosity favors a reduction in the value of the pressure difference, which can be seen in the first 0.14 s (Figure 8a), when the bed reaches the first valley of pressure drop at 0.18 s (Figure 8b). From this instant on,

a sharp increase in pressure drop is seen and reaches a largest peak at 0.2 s. This fact can be explained by the particles dropping simultaneously, thus reducing the empty spaces or porosity of the bed and leading to an increase in resistance to the gas flow through the spouted bed. The other peaks and valleys follow a similar behavior, being related to the pressure exerted by the particles in the gas inlet region, Ramos (2018) and Borges (2011) saw this behavior.

The formation of the source region occurs at 0.44 s for the equipment without a suction tube, and 0.98 s for the spouted bed with a suction tube. This difference is a consequence of the geometric shape of the particle and the direction of the gas flow that affect the drag forces. Therefore, a stabilization of the source region in the spouted bed is seen. In a time, equal to 0.14 s is reached from the maximum pressure drop, the particles change direction and travel in the opposite direction to the gas and return to the annular region. Thus, leading to an increase in pressure in the spouted bed inlet section.

In Figure 8b, the behavior of the particles is like that seen in Figure 8a, at the following time instants: 0.2; 0.46s. However, after $t=2$ s, the air flow rate occurred stability in both.

4. CONCLUSION

The mathematical modeling was represented the fluid dynamic behavior of the spouted bed being possible to clearly see the annular, spout and fountain regions.

The results confirm that the use of the draft tube favors the formation of the spouted bed.

The evolution of the pressure drops in the spouted bed over time showed different behaviors of the spouted bed with and without the suction tube.

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