UNIVERSIDAD SAN FRANCISCO DE QUITO

Colegio de Ciencias e Ingeniería

Hydrodynamic Study for a Granular Material Used in Pack Carburizing Processes in a Cold Fluidized Bed

Trabajo experimental

Michaelle Alejandra Pazmiño Pazmiño

Ingeniería Mecánica

Trabajo de titulación presentada como requisito de la obtención del título de Ingeniero Mecánico

Quito, 13 de Mayo de 2016

UNIVERSIDAD SAN FRANCISCO DE QUITO USFQ

COLEGIO DE CIENCIAS E INGENIERIA

HOJA DE CALIFICACION DE TRABAJO DE TITULACION

Hydrodynamic Study for a Granular Material Used in Pack Carburizing Processes in a Cold Fluidized Bed

Michaelle Alejandra Pazmiño Pazmiño

Calificación:

Nombre del profesor, Título académico David Escudero, P.h.D.

Firma del profesor ____________________________________

Quito, 13 de Mayo de 2016

Derechos de Autor

Firma del Estudiante: ___________________________________

Nombres y apellidos: Michaelle Alejandra Pazmiño Pazmiño

Código: 00106885

Cedula de Identidad: 1417963798

Lugar y fecha: Quito, Mayo de 2016

AGRADECIMIENTO

A David Escudero P.h.D; mi director de trabajo de titulación por liderar este proyecto y por su apoyo durante mi carrera de Ingeniería Mecánica en la USFQ.

A mi papá Patricio, mi mamá Irlanda y mi hermana Stefany por brindarme su apoyo incondicional en mi vida personal y académica.

A todos mis amigos de la USFQ y al personal docente de Ingeniería Mecánica.

RESUMEN

El objetivo de este proyecto es el estudio hidrodinámico de un material granular que sirve para procesos de cementación por empaquetamiento en un lecho fluidizado frio. Este estudio se enfoca en la clasificación de las partículas de Geldart, el cálculo de los parámetros de fluidización y el comportamiento del material expuesto a diferentes rangos de flujos. Basado en métodos de resultados experimentales y correlaciones matemáticas, los resultados fueron comparados y los regímenes de fluidización fueron encontrados. Los resultados muestran que el valor de la mínima velocidad de fluidización fue de $u_{mf} = 9.99\ \frac{cm}{s}$ mediante los resultados experimentales y $u_{mf} = 2.17\ \frac{cm}{s}$ mediante correlaciones matemáticas. Estos resultados son importantes para predecir el comportamiento de la fluidización y se puede analizar las propiedades del material granular, las propiedades del fluido y del diseño del reactor para mejorar el diseño experimental.

ABSTRACT

The focus of this project was the hydrodynamic study of a granular material that is used in pack carburizing processes in a cold fluidized bed. This study emphasis in the classification of the Geldart's particles, the estimation of the fluidization parameters and the behavior of the material exposed to different flow rates. Based on the methods of experimental results and mathematical correlations; results were compared and fluidization regimes were found. The results shows that the value of the minimum fluidization velocity was $u_{mf} = 9.99\ \frac{cm}{s}$ by experimental results and $u_{mf} = 2.17\ \frac{cm}{s}$ by mathematical correlations. These results are important to predict the behavior of the fluidization and to improve the experimental design by analyzing the properties of the material, the properties of the fluid and the reactor's design.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1. Introduction

1.1. Motivation

The surface hardening of metallic materials is a very important part for the mechanical industry and is essential to find new tools, techniques and technologies to optimize and improve mechanical processes to obtain the desired properties in accordance with the requirements of manufacturing and design. The substrate treatment is a method used in materials science for surface hardening of metals, altering the chemical composition of the surface layer, placing mixtures hardening elements as combined coal with calcium carbonate, sodium or barium by a diffusion process reaches a cementing material (Rodriguez, 2007). Pack carburizing allows hardening in the surface layer of the material to improve its mechanical properties. This process despite being the oldest and have limitations offers ideal solutions with excellent results especially for small industry where it is not required for mass production (Ferrero, 2012).

Fluidization is an option to improve the pack carburizing process and depends on properties of the solid material and fluid to find the optimal parameters that will provide an excellent performance of the fluidized bed (Conesa, n.d.). Fluidization has helped to eliminate certain difficulties inherent in the gasification of coal ash fuse leading to the temperature of work and has been very efficient to work in fields of mining and metallurgy as density classification, sedimentation and liquid separation (Hernandez, 2009). Fluidized bed reactors have several advantages such as excellent heat transfer rates, good solid-gas mass transfer, low-pressure drop and easy solids handling (J. Ruud van Ommen & Naoko Ellis, 2010). With the hydrodynamic study of granular material, we want to predict the overall behavior of the fluidization where parameters such as temperature, pressure of the reactor, gas flow and particle diameter strongly influence the fluidization of the material in the fluidized bed.

1.2. Objectives

Based on the justification and importance of the motivation for this work, the general and specific objectives are as follows:

1.2.1. General objectives

Understand the hydrodynamic behavior of a granular material used in pack carburizing processes in a cold flow fluidized bed.

1.2.2. Specific objectives

- Classified the granular material using the Geldart's particles classification.

- Determine the minimum fluidizing velocity, the maximum fluidizing velocity and the bubbles size for a granular material composed by 90% activated carbon and 10% calcium carbonate.

- Visualized the granular material behavior at different fluidizing velocities rates.

1.3. Overview

The following document presents the study and research that meets the objectives described in the previous section. Chapter 2 describes all the theoretical concepts related to fluidization and parameters of the fluidized bed. Chapter 3 details all equipment, methods and experimental procedure used to collect outcome data. Chapter 4 analyzes and discusses the results obtained. Chapter 5 mentions the conclusions and possible recommendations for future projects.

2. Reviewing Concepts

2.1. Fluidization

Is the phenomenon that occurs when a bed of small solid particles is suspended in an upward-flowing liquid or gas stream (Fogler, 2006) (Barreira, 2007). The bed is fluidized when the velocity of the gas is increasing and the particles are suspended in the stream.

Fluidization has been used since 1944 in commercial operations such as fluid catalytic cracking and fluidized beds combustors (Yang, 1999). Depending on the type of reaction, fluidized beds have several industrial applications in metallurgical, chemical and other processes. In this work, the focus is on gas-solid systems, which are divided into the following categories: gas catalytic reaction, gas-phase reaction, gas-solid reaction, and the last one where no chemical reactions occur (Escudero, 2014).

Although new technology provides with the prediction and knowledge to understand fluidization, engineers still face with problems when they develop new commercial designs and research is needed. Besides, it would be helpful to design small units that could be used to solve problems and optimize the commercial plants (Yang, 1999).

2.1.1. Fluidized beds

Fluidized beds are reactors where occurs the fluidization of solid particles (Escudero, 2014). We consider a vertical bed when the direction of the gas flow is upward and supported by a porous distributor plate. In figure 2.1, we can see the different fluidization regimes that occur in a fluidized bed (Fogler, 2006).

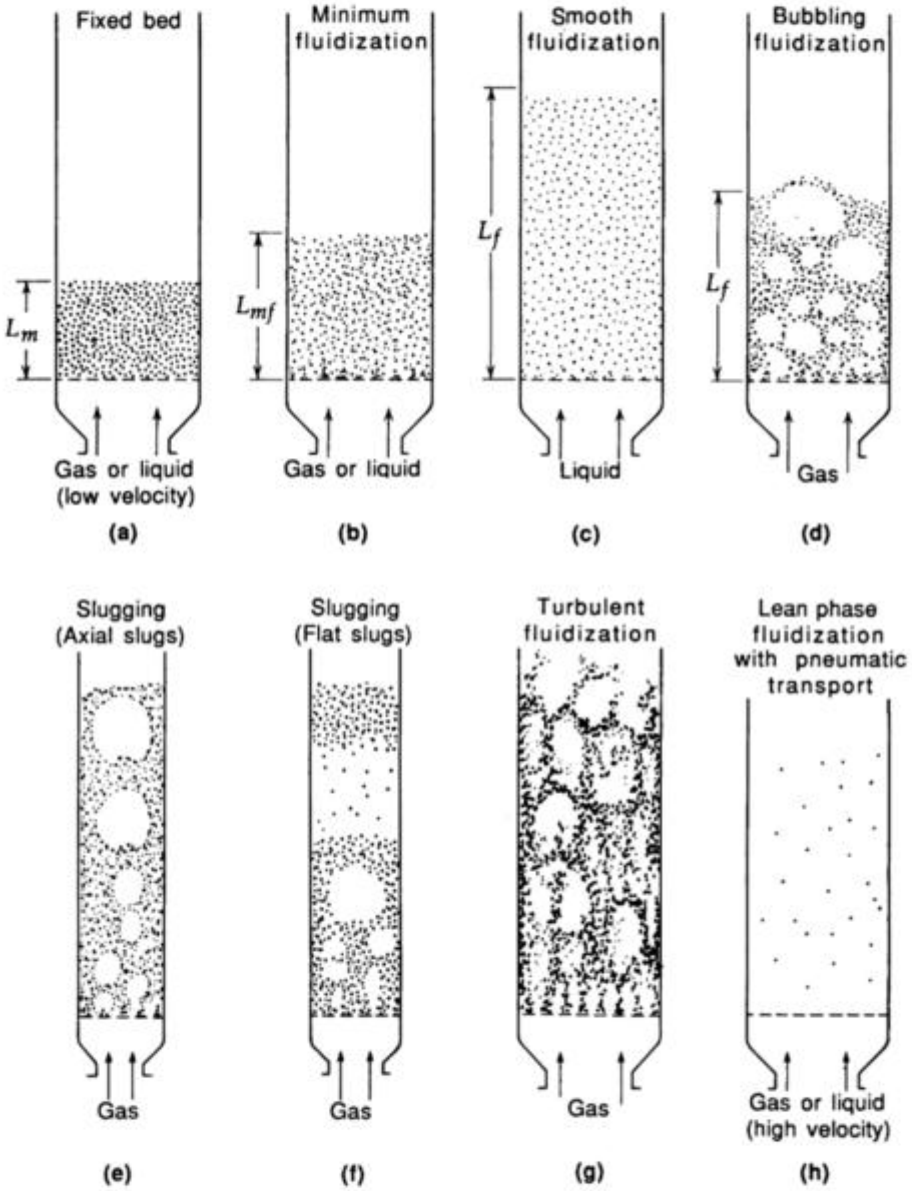

Figure 2.1: Fluidization Regimes (Daizo Kunii, Octave Levenspiel , 1991)

A fixed bed is when, at a low flow rate, the fluid passed upward through a bed of solid particles as shown in Fig.2.1 (a). The fluid pass through the empty spaces between the stationary particles. The minimum fluidization regime in Fig.2.1 (b) occurs when the flow has a higher velocity and all the particles are suspended by the upward-flowing liquid or gas; at this point, the weight of the particles counterbalance the drag force between the fluid and the particles. As the flow rate passes beyond the minimum fluidization velocity the gas-solid system has large instabilities, it is observed in the solid some bubbling, and channeling, this happens in the smooth fluidization as shown in Fig.2.1 (c). Moreover, a bubbling fluidized bed occurs at higher flow rates; see in Fig.2.1 (d). The movement of particles becomes more vigorous and the agitation more violent. Furthermore, the gas bubbles coalesce and it causes that the particles begin to rain down by the reactor's wall around the empty spaces of the bed; this is the slugging with axial slugs regime, showed in Fig.2.1 (e). In addition, in Fig.2.1 (f) solids disintegrate when they flow down from the slug, this type of fluidization is slugging with flat slugs. Additionally, the turbulent fluidization appears when the terminal velocity is exceed in the bed and you can observed several voids of gas with different sizes and shapes, as shown in Fig.2.1 (g). Finally, the lean phase fluidization with pneumatic transport of solids appear. The high further increase of fluid velocity causes the fine particles to entrain out of the bed with the gas; see Fig.2.1 (h) (Daizo Kunii, Octave Levenspiel , 1991).

For this study, the focus is purely on the minimum and bubbling fluidization regimes. This will allow us to visualize the behavior of the particles at flow rates higher than the minimum fluidization velocity.

2.1.2. Minimum fluidization velocity (u_{mf})

Considering an upward-flowing fluid passing through a bed of solid particles, the fluid velocity will increase until it reaches a value where the particles are suspended by the stream of gas fluid. This value is the minimum velocity needed to begin the fluidization (Levenspiel, 1987).

The minimum fluidization velocity depends on numerous conditions such as fluid properties, size and shape of the fluidized bed and material properties. These parameters are important because they stablish the hydrodynamic behavior of the different fluidized regimes and its inferior limits of fluidization (Escudero, 2014) (Keller, 2012).

There are three experimental methods to estimate the value of U_{mf}:

- *Heat transfer method*: this method computes the value of the minimum fluidization velocity when the superficial gas velocity increases and there is a variation of the heat transfer coefficient in the wall of the bed (Escudero, 2014).
- *Voidage method*: the U_{mf} can be calculated when the voidage of the bed begins to increase because of the bed expansion while the superficial gas velocity rise (Escudero, 2014).
- *Drop pressure method*: It is represent by the function of superficial gas velocity vs pressure drop. While the superficial gas velocity increase, the pressure drop increases until it reaches a point of transition between the fixed and bubbling regimes (Figure 2.2), this point represents the U_{mf} and the maximum value for pressure drop remains constant as superficial gas velocity increases (Escudero, 2014) (Keller, 2012).

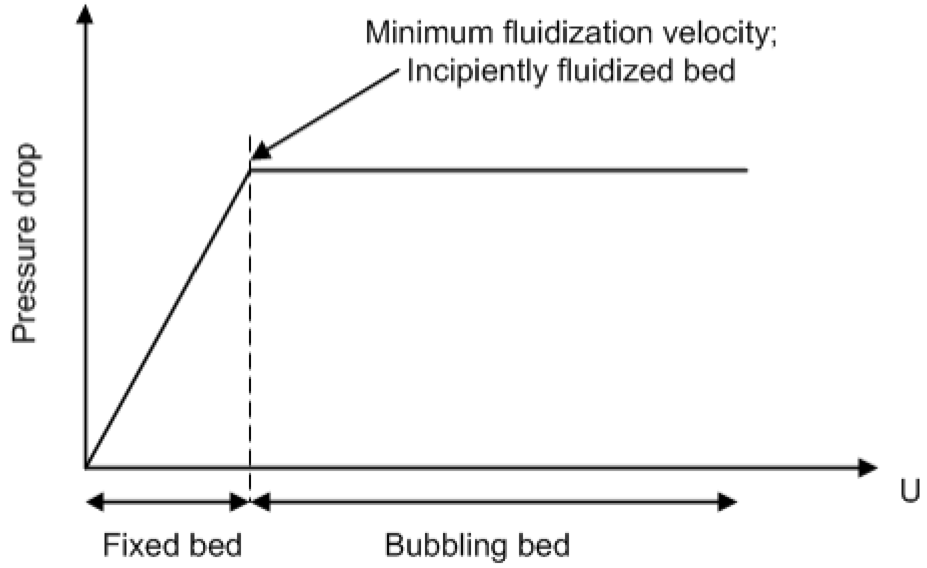

Figure 2.2: Pressure Drop vs Superficial Diagram (Keller, 2012)

Drop pressure method is the most common procedure to determine the minimum fluidization velocity and there are mathematical correlations to calculate this velocity as establish by Fogler. (Fogler, 2006) (Castellanos, 2015).

Fluidization will begin at the gas velocity at which the weight of the solids gravitational force exerted on the particles equals the drag force on the particles from the rising fluid. Consequently, when the weight of the solid material is equal to the pressure drop across the bed (Fogler, 2006), the equation to calculate the minimum fluidization velocity is:

$$u_{mf} = \frac{\psi d_p{}^2}{150\mu} g(\rho_p - \rho_g) \frac{\varepsilon_{mf}^3}{1-\varepsilon_{mf}} \qquad (2.1)$$

where $\boldsymbol{\mu}$ is the dynamic viscosity of the fluid, $\boldsymbol{d_p}$ is the particle diameter, $\boldsymbol{g}$ is the gravity, $\boldsymbol{\rho_p}$ is the particles density and $\boldsymbol{\rho_g}$is the fluid density.

Besides, the two dimensionless parameters of the previous equation are sphericity $\boldsymbol{\psi}$ and porosity of the fluid bed $\boldsymbol{\varepsilon_{mf}}$. These two correlations are represent in the following equations:

$$\psi = \frac{\pi \, {\frac{6V_p}{\pi}}^{\frac{2}{3}}}{A_p} \tag{2.2}$$

where, 0.6 is a normal value that can be assumed for a typical granular material.

$$\varepsilon_{mf} = 0.586\psi^{-0.72} \; {\frac{\mu^2}{\rho_g \eta {d_p}^3}}^{0.029} \; {\frac{\rho_g}{\rho_p}}^{0.021} \tag{2.3}$$

2.1.3. Maximum Fluidization Velocity ($\boldsymbol{u_t}$)

When the velocity of the gas reaches a high value, the gravitational force will be less than the drag of the solid particle. Consequently, the particle will be entrained in the gas stream and carried out of the fluidized bed. As a result, the upward gas velocity will have a higher value than the free-fall terminal velocity, u_t. For estimated this value, exist two relationships presented by the Kunii and Levenspiel Model (Fogler, 2006).

$$u_t = \frac{\eta {d_p}^2}{18\mu} \qquad Re < 0.4 \tag{2.4}$$

$$u_t = \; {\frac{1.78x10^{-2}\eta^2}{\rho_g \mu}}^{1/3} \; d_p \qquad (0.4 < Re < 500) \tag{2.5}$$

where, the Reynolds number and η the gravitation term can be calculated with the following equations:

$$Re_p = \frac{d_p \rho_g u_{mf}}{\mu} \tag{2.6}$$

$$\eta = g(\rho_p - \rho_g) \tag{2.7}$$

2.1.4. Maximum Bubble Diameter (d_{bm})

When the bed is enough higher, Fogler says that "the maximum bubble diameter, d_{bm}, attained if all bubbles in any horizontal plane coalesce to form a single bubble" (Fogler, 2006). As a result, d_{bm} has the following mathematical correlation:

$$d_{bm} = 0.652\ A_c\ u_o - u_{mf}\ ^{0.4} \tag{2.8}$$

where A_c is the cross sectional area, u_o is the entering superficial velocity and u_{mf} is the minimum fluidization velocity.

In effect, the bubbles size depend on factors such as bed diameter, gas velocity, height above the distributor plate and the components that affect fluidization. Additionally, this phenomenon can explain the behavior of the bed material in the reactor when the bubbles carry each other up in the stream and present larger amounts of gas passing through the bed (Fogler, 2006).

2.1.5. Minimum Bubble Diameter (d_{b0})

The minimum bubble size can be obtained by using the next correlation for perforated plates (Fogler, 2006):

$$d_{b0} = 0.347\ \frac{A_c\ u_o - u_{mf}}{n_d}\ ^{0.4} \tag{2.9}$$

where, n_d is the number of perforations of the aeration plate.

2.1.6. Relationship between Bubble Diameter and Height in the Column

This relationship allows the calculation of the average bubble diameter, d_b, and the following equation shows that the bubbles grow as they rise through the bed (Fogler, 2006).

$$\frac{d_{bm} - d_b}{d_{bm} - d_{bo}} = e^{-0.3h/D_t} \tag{2.10}$$

2.1.7. Bubble velocity

The rise velocity of a single bubble in a fluidized bed can be related by the next mathematical correlation:

$$u_{br} = (0.71)(gd_b)^{1/2} \tag{2.11}$$

In addition, the rise velocity of a bubble when more bubbles are present (Fogler, 2006) is represented by the next equation:

$$u_b = u_o - u_{mf} + (0.71)(gd_b)^{1/2} \tag{2.12}$$

2.2. GELDART's particles classification

The behavior of the bed is characterized by the size and density of the solid particle (Figure 2.3). Since not every particle can be fluidized, Geldart mention four types of particles.

Group A: the particles have small diameter and low density $< 1.4\ \frac{g}{cm^3}$. These particles fluidized easily and do not make bubbles even at high flow velocity.

Group B: the particle diameter has a value between 40 to 550 μm and its density among $1.4 < \rho < 4\ \frac{g}{cm^3}$. The particles fluidized good and they have large size bubbles.

Group C: the diameter of the particles are between $10 < d_p < 40\ \mu m.$ The particles are powders and very cohesive. They are extremely difficult to fluidize.

Group D: the diameter and the density are large and the particles are heavy.

For this particular study the granular material used is classify as a Geldart type A particle.

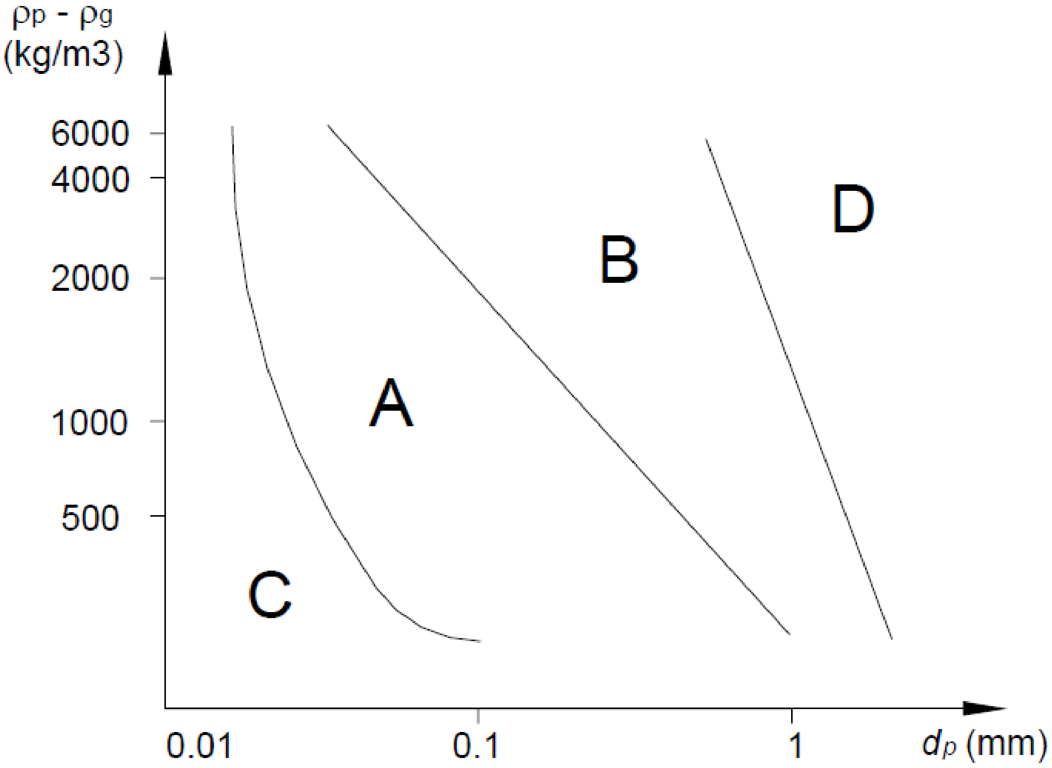

Figure 2.3: Geldart's particles classification (Conesa, n.d.)

3. Experimental Setup

This chapter explains the equipment, procedures and techniques that were used in this work. In section 3.1, emphasize the basic equipment that was applied in the research including the fluidized bed reactor, air system and the instrumentation to measure the gas flow. In section 3.2, describes the selection and classification of the material. Finally in section 3.3, summarizes the techniques and experimental procedures used to determine the minimum fluidization velocity.

3.1. Basic Equipment

This section explains all the equipment that was utilized to determine the minimum fluidization velocity. Include the fluidized bed reactor, the air system and the instruments to measure the pressure and the gas flow.

3.1.1. Fluidized Bed Reactor

The reactor used in this experimental research is a cold flow fluidized bed reactor. This equipment was designed by Luis Castellanos in his thesis. The fluidized bed reactor has three main chambers: the top chamber, the bed chamber and the plenum, see in Fig 3.1. The fluidized bed was fabricated with an acrylic tubing that its external diameter is 10.5 cm and the wall thickness is 0.5 cm. These dimensions are from the plenum and the bed chamber. Besides, the top chamber was made with a PVC tube and it has an 11 cm external diameter. Lastly, there is an aeration plate where the fluid pass through the system and is located between the plenum and the bed chamber with 132 perforations (Castellanos, 2015).

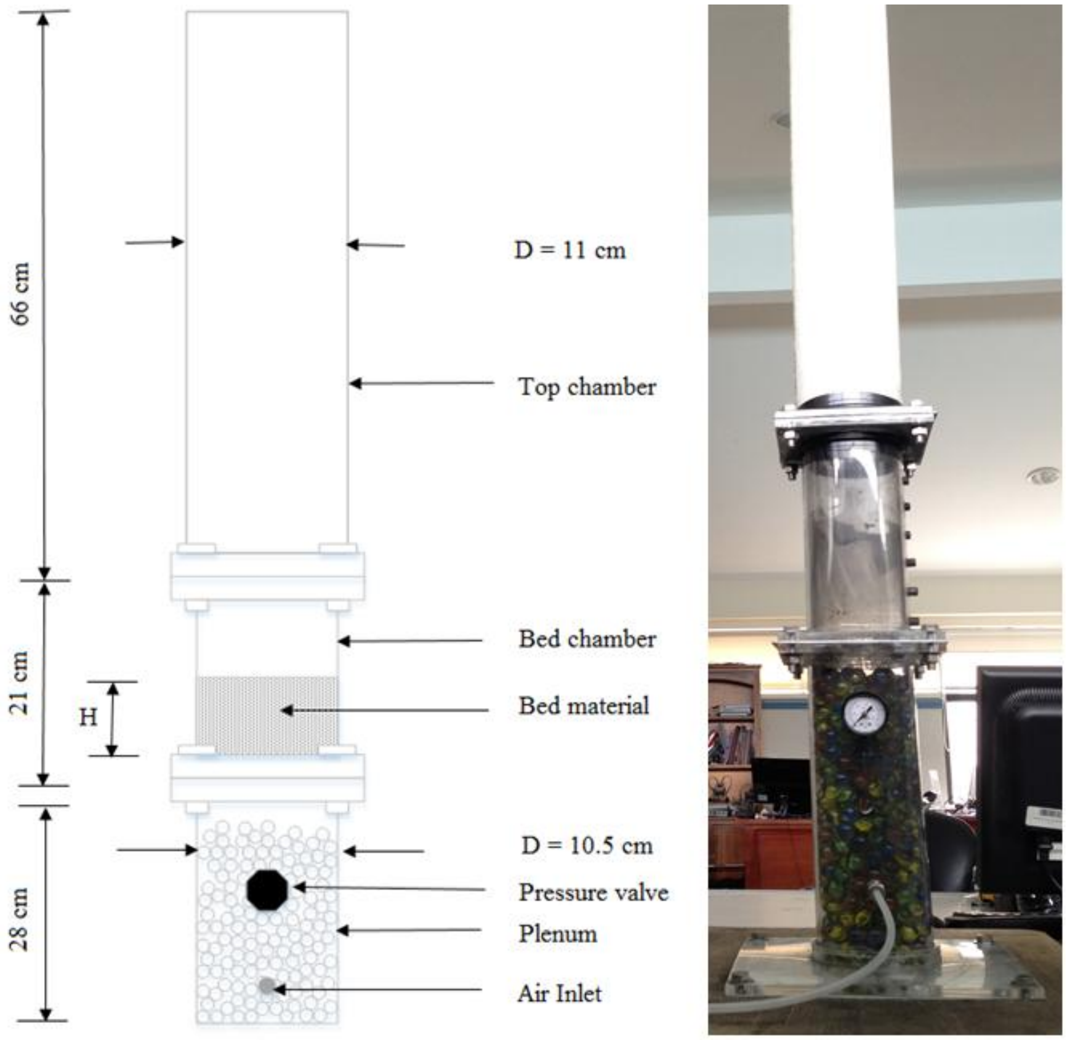

Figure 3.1: Fluidized Bed Reactor's Dimensions (not to scale)

Fluidization takes place in the bed chamber which is 21 cm tall and H is the static bed height of the solid material with a value of 9.5 cm. In the other hand, the pressure valve and the air inlet are located in the plenum, which is 28 cm tall.

3.1.2. Air System

The fluidizing gas in this study is the filtered compressed air supplied by the mechanical laboratory of the university. Usually the pressure of the fluid in the laboratory is 70 PSI. In order to calculate the minimum fluidization velocity it is necessary and important to vary the flow rates according to the specific conditions of the experiment and the use of valves to regulate the flow and the pressure are basic in the experimental setup.

In consequence, volumetric flow rate is measure with an instrument called flow meter and it can estimated flows up to 10 SCFM (Standard Cubic Feet per Minute), as shown in Figure 3.2. In the other hand, a pressure regulator controlled the pressure of the air passing through the system and it was set to 15 psi, see in Figure 3.3.

Figure 3.2: Mass Flow Meter

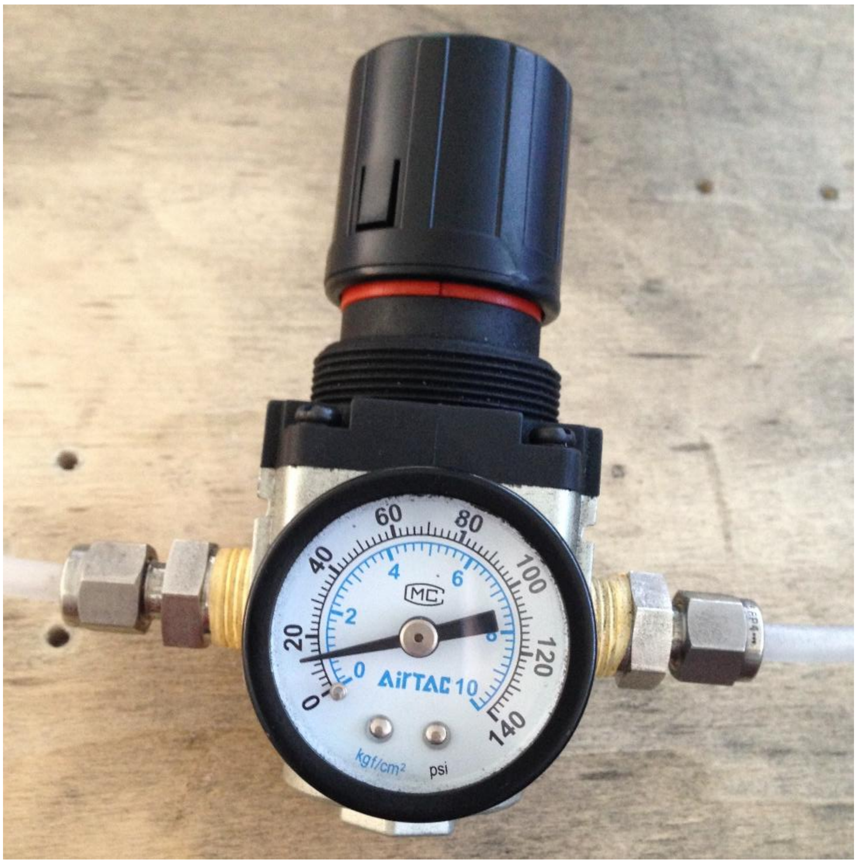

Figure 3.3: Pressure Regulator

3.2. Bed Material

This section shows the criteria used to select and classifies the material for the experimental research. This is important because the materials parameters have a significant influence in the behavior of the fluidization.

3.2.1. Selection of the Material

The material used in this research is based on solid carburizing processes; for this reason many types of carbon can be used in this process such vegetable carbon, wood carbon, activate carbon and coke. However, no good results are obtained using only carbon in the carburizing processes, so it is better to combine carbon with the use of an activator material such as calcium carbonate $CaCO_3$, sodium carbonate Na_2CO_3 , barium carbonate $BaCO_3$, or potassium carbonate K_2CO_3 . Indeed, several combinations conform a carburizing mix, see in table 3.1 (Carrillo, 2015).

Table 3.1: Elements of Carburizing Mix (Carrillo, 2015).

CARBURIZING	ELEMENTS	WEIGHT PARTS
Compound no. 1	Carbon	**90 %**
	Calcium carbonate	**10 %**
Compound no. 2	Barium carbonate	**10 %**
	Carbon	**90 %**
Compound no. 3	Carbon	**50 %**
	Coke	**30 %**
	Barium carbonate	**12 %**
	Sodium carbonate	**3 %**
	Calcium carbonate	**3 %**
	Agglutinant	**2 %**

For this study, the focus is purely on compound no. 1.

It is very important to mention that the density of the compound is in the range of 450 – 500 $\frac{kg}{m^3}$ according to the supplier of the material.

3.2.2. Classification of the Material

To determine the particle's diameter of both materials, the procedure that was used is by using several mesh sieves, as shown Fig.3.2. With the use of a mechanical shaker, the particles were divided into different sizes according to the mesh size used. The activated carbon and the calcium carbonated vibrated for about 5 minutes in the mechanical shaker but the process was not repeated since carbon is very fragile. Table 3.2 stablish the sizes of the diameters of each mesh.

Figure 3.4 Mechanical Shaker

Table 3.2: Mesh sizes in microns and millimeters

MESH	DIAMETER	
No.	$[\mu m]$	$[mm]$
16	1190	1.190
30	595	0.595
50	297	0.297
100	149	0.149
140	105	0.105
200	74	0.074

Based on Geldart classification, to have a good fluidization the particles must be in-group A; according to figure 2.3, the desire diameter is between $0.1 - 1$ $[mm]$. In consequence, the bed material used was from mesh number 100. For this reason, the distribution of the particle diameter is between 0.149 – 0.297 mm.

3.3. Procedure for the Minimum Fluidization Velocity

To fulfill the experimental research objectives, this work will follow the next methodology that explains by visual observation the behavior of the solid particles in the material chamber and its fluidization regimes. It is important to emphasize that 20 experiments were made, and each experiment present a variation of the air flow, from 8 SCFM to 0 SCFM, to observe all the resultant fluidization regimes. First, the compressor deliver the gas fluid to the fluidized bed, the flow meter controls the required quantity of air and the pressure regulator adjusts the desire air pressure. Then, the flow rate was set to 8 SCFM until it reaches a steady state and it was observed the behavior of the solid particles in the bed chamber. Later, the flow rate was reduced in intervals of 2 SCFM. This process was repeated until there was no air passing through the bed.

The reason why the experiment begin with 8 SCFM until it reaches the lower flow rate at 1 SCFM was to avoid packing effect. It means that is more difficult to see the behavior of the solid particles at the beginning since they are joint together and they need a higher flow rate to be fluidize and be separate. Therefore, to have a better results we decided to begin with a high flow rate to move all the material in the bed chamber and detect a better behavior of the solid particles in the fluidized bed.

4. Experimental Results and Discussion

4.1. Fluidization Parameters Data Using Correlations

Using the equations from section 2.1 and all the properties of the granular material, reactor and the fluid, as shown in table 4.1, the fluidization parameters can be calculated and compared with the experimental results.

Table 4.1: Data of the granular material properties, reactor design and fluid properties

Data	Value [units]
Particle diameter, d_p	$0.0223\ cm\ (mean\ diameter)$
Sphericity, ψ	$0.6\quad assumed$
Particle density, ρ_p	$0.475\ \frac{g}{cm^3}$
Bed diameter, D_t	$9.5\ cm\quad internal\ diameter$
Number of perforation in the aeration plate, n_d	132
Height of the material in the bed chamber, h	$9.5\ cm$
Gas density, ρ_g	$0.001205\ \frac{g}{cm^3}$
Fluid viscosity, μ	$1.86 * 10^{-4}\ \frac{g}{cm \cdot s}$

To calculate the minimum fluidization velocity the following procedure is used:

First, the Gravitational term, η is obtained

$$\eta = 980\frac{cm}{s^2}\ \ 0.475\frac{g}{cm^3} - 0.001205\frac{g}{cm^3}$$

$$\eta = 464.32\ \frac{g}{s^2 cm^2}$$

Follow by the porosity of a minimum fluidization bed, ε_{mf}

$$\varepsilon_{mf} = \ 0.586 \quad 0.6^{-0.72} \quad \frac{1.86 * 10^{-4}\, g \quad cm \cdot s \ ^{2}}{0.001205\, g \quad cm^{3} \quad 464.32\, g \quad s^{2}cm^{2} \quad 0.0223cm \ ^{3}}^{\ 0.029}$$

$$* \ \frac{0.001205\, g \quad cm^{3}}{0.475\, g \quad cm^{3}}^{\ 0.021}$$

$$\varepsilon_{mf} = 0.64$$

As a result, the minimum fluidization velocity, u_{mf}, is calculated:

$$u_{mf} = \frac{(0.6 * 0.0223cm)^{2}}{(150)(1.86 * 10^{-4}\, g \quad cm \cdot s)} * \quad 464.32\, g \quad s^{2}cm^{2} \quad * \frac{0.64^{3}}{1 - 0.64}$$

$$u_{mf} = 2.17 \ \frac{cm}{s}$$

The entering gas velocity, u_o which is the highest experimental velocity used is calculated based on the flow rate and the cross sectional area of the fluidized bed

$$Q = 8\, scfm \ \rightarrow 3775.6 \ \frac{cm^{3}}{s}$$

$$u_o = \frac{Q}{A} = \frac{3775.6\, cm^{3} \quad s}{\frac{\pi * (9.5\ cm)^{2}}{4}}$$

$$u_o = 53.27 \ \frac{cm}{s}$$

Futhermore, to calculate the maximum fluidization velocity the next method was used:

The Reynolds number, Re_p is calculated:

$$Re_p = \frac{(0.0223\ cm)(0.001205\, g \quad cm^{3})(2.17\, cm \quad s)}{(1.86 * 10^{-4}\, g \quad cm \cdot s)}$$

$$Re_p = 0.31$$

So, for a 0.31 Reynolds number equation 2.6 it’s used.

As a result, the maximum fluidization velocity, u_t, is:

$$u_t = \frac{(464.32\, g\ \ s^2 cm^2)(0.0223 cm)^2}{18(1.86 * 10^{-4}\, g\ \ cm \cdot s)}$$

$$u_t = 68.96\ \frac{cm}{s}$$

Besides, the average bubble size is determine with the following mathematical correlations.

Minimum bubble size, d_{bo}

$$d_{bo} = 0.347\ {\frac{\frac{\pi * (9.5\ cm)^2}{4}\ \ 53.26\, cm\ \ s - 2.17\, cm\ \ s}{132}}^{0.4}$$

$$d_{bo} = 1.31\ cm$$

Maximum bubble size, d_{bm}

$$d_{bm} = 0.652\ {\frac{\pi * (9.5\ cm)^2}{4}\ \ 53.26\, cm\ \ s - 2.17\, cm\ \ s}^{0.4}$$

$$d_{bm} = 17.29\ cm$$

Since this value is larger than the bed chamber diameter, slugging will occur.

Average bubble size, d_b

$$\frac{17.29\ cm - d_b}{17.29\ cm - 1.31\ cm} = e^{\frac{-0.3*9.5}{9.5}}$$

$$d_b = 5.46\ cm$$

Finally, the velocity of a single bubble is estimated.

Rise velocity of a single bubble, u_{br}

$$u_{br} = (0.71)(980\,cm\ \ s^2 * 5.45\ cm)^{1/2}$$

$$u_{br} = 51.94\ \frac{cm}{s}$$

Rise velocity of a single bubble when more bubbles are present, u_b

$$u_b = \ \ 53.26\,cm\ \ s - 2.17\,cm\ \ s\ \ +\ \ 0.71\ \ \ 980\,cm\ \ s^2 * 5.45\ cm^{\ \frac{1}{2}}$$

$$u_b = 103.04\ \frac{cm}{s}$$

It is important to emphasize that values of the size and the velocity of the bubble depend purely on the entering flow rate. For this reason, the following table 4.2 tabulated all the bubble sizes and velocities taken for each flow rate of the experiments.

Table 4.2: Bubble Size and Velocity for each Flow Rate

Q		u_o $[cm\ \ s]$	d_{bo} $[cm]$	d_{bm} $[cm]$	**Fluidization Regimes**	d_b $[cm]$	**Velocity of a Single Bubble**	
(SCFM)	**(cm^3/s)**						$u_{br}\ [cm\ \ s]$	$u_b\ [cm\ \ s]$
8	3775,60	53,27	1,31	17,29	Slugging	5,46	51,94	103,04
6	2831,68	39,95	1,16	15,32	Slugging	4,84	48,90	86,68
4	1887,79	26,63	0,97	12,88	Slugging	4,07	44,83	69,29
2	943,90	13,32	0,71	9,40	No slugging	2,97	38,31	49,45
1,5	707,92	9,99	0,62	8,16	No slugging	2,58	35,68	43,50
1	471,95	6,66	0,49	6,54	No slugging	2,06	31,93	36,42

4.2. Comparison between experimental and correlations u_{mf}

Based on the visual observation, 20 trials were performed and it was observed that the fluidization had stop fluidizing in the bed chamber with an entering superficial velocity of $u_o = 6.66\ \frac{cm}{s}$ corresponding to the flow rate of $1\ SCFM$. This is an approximate solution, a more accurate procedure will be using the drop pressure method, however this method was not used because the pressure manometer had a range that was higher than the pressure exerted by the material so it was not possible to read the pressure drop across the bed.

With the previous mathematical correlations, the superficial velocity in the fluidized bed and the average bubble size were calculated with the corresponding volumetric flow.

The following table 4.3 shows the experimental results and the calculations with the mathematical correlations obtained in the previous section for the minimum and maximum fluidization velocity.

Table 4.3: Comparison between Experimental Results with Mathematical Correlations of the Minimum Fluidization Velocity

	Experimental Results $Q = v * A$	**Mathematical Correlations**
u_{mf}	$u_{mf} = 9.99\ \frac{cm}{s}$	$u_{mf} = 2.17\ \frac{cm}{s}$
u_t	$u_t = 53.27\ \frac{cm}{s}$	$u_t = 68.96\ \frac{cm}{s}$

As the precision of the flow meter was not accurate because it had higher divisions of the flow passing through the system than the flow rates that this experiment needs, the trial results have a normal experimental error and the difference of the estimated values are not to altered between the two of them. In addition, many assumptions were taken along in the calculation of the mathematical correlations and properties of the material used in the previous section, such as the average particle diameter and granular material density. As a result, this also affect to get an accurate value of each velocity.

4.3. Visual Observation of the Fluidizing Regimes

Using the methodology explained in section 3.3 the different fluidization regimes of the granular material was observed. At the flow rate of 8 SCFM it was observed that all the granular material in the bed chamber was fluidizing with a high velocity, a violent agitation and partially all the particles move in the reactor in a homogeneous way. Besides, some bubbles were coalesced in the reactor’s wall forming empty spaces inside the granular material around the bed. Consequently, a bubbling and slugging fluidization regime was found in this phase, as shown in Fig 4.1.

Figure 4.1: $\dot{Q}$=8 [SCFM] and u_o=53.27 [cm ⁄s]

Then, the air flow value was decreased to 6 SCFM; where the flow rate velocity was also high and particles were vigorously moving, presenting similar characteristics to the previous stage, however not all the material had a homogeneous movement since all the experiments show that the granular material fluidized completely in half of the reactor's walls. Based on these conditions, the fluidizing regime was the bubbling fluidized bed in Fig 4.2.

Figure 4.2: $\dot{Q}$=6 [SCFM] and u_o=39.95 [cm/s]

Later, the airflow at 4 SFCM was set and the behavior that was saw indicated that part of the granular material was fluidized, but some granular material stay without fluidizing in the base of the bed chamber because of its slower flow. Furthermore, it seemed that air made some channels to pass through the solid material, but it was a consequence of small bubbles coalescing and exiting the granular material. As a result, in this point, the regime still characterized as a bubbling fluidized bed, see in Fig 4.3.

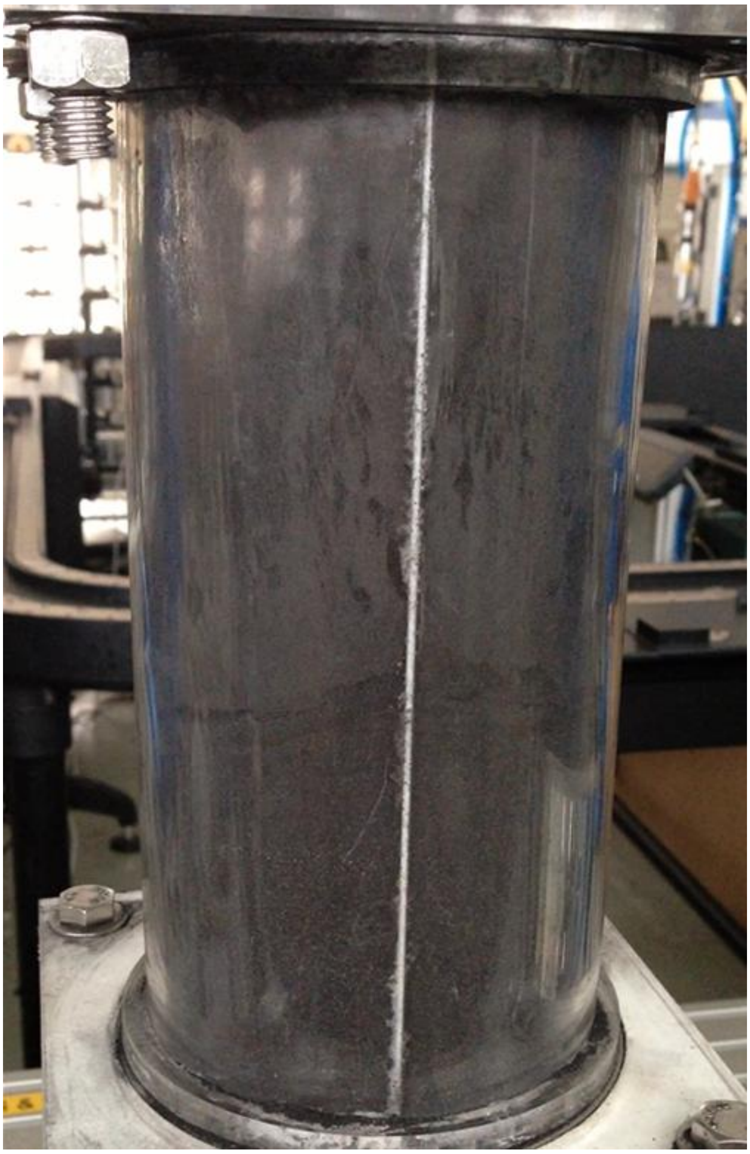

Figure 4.3: $\dot{Q}$=4 [SCFM] and u_o=26.63 [cm⁄s]

Next, the flow rate decreased at 1.5 or 2 SCFM depending the situation of each experiment, where it was observed that almost all the granular material stay without fluidizing and the fluid pass through the empty spaces between the stationary particles, but then a small quantity of particles were suspended by the upward-flowing air and presented some channeling. At this point, minimum fluidizing regime occurs as shown in Fig 4.4.

Figure 4.4: $\dot{Q}=2$ ***[SCFM] and*** $u_o=13.32$ ***[cm]⁄[s]***

Finally, the flow rate was set on 1 SCFM and it exposed that the low flow rate didn't make the particles fluidized so all the particles stay stationary in the bed. In consequence, a fixed bed regime was present, see in Fig 4.5.

Figure 4.5: $\dot{Q}$=1 [SCFM] and u_o=6.66 [cm]⁄[s]

In addition, the following table 4.4 has made the comparison between the visual observation and the mathematical correlations calculated in table 4.2 for the fluidized regimes.

Table 4.4: Comparison between Visual Observation and Mathematical Correlation for Fluidizing Regimes

Flow Rate	Visual Observation	Mathematical Correlation
8 SCFM	Bubbling and Slugging Fluidization	Slugging Fluidization
6 SCFM	Bubbling Fluidization	Slugging Fluidization
4 SCFM	Bubbling Fluidization	Slugging Fluidization
1.5 - 2 SCFM	Minimum Fluidizing	No Slugging Fluidization
1 SCFM	Fixed Bed	No Slugging Fluidization

In summary, the comparison made between the two distinct procedures was very close and it demonstrate that the 3 higher flows rates of 8- 6- 4 SCFM had a slugging fluidization regime but also present characteristics of bubbling fluidization regime such as the violent and strong agitation and the particles seems to move very vigorous. On the other hand, in the phase of 2- 1,5 SCFM visually presented the minimum fluidization regime because not all the material fluidized completely such as the other flow rates. Nevertheless, in the flow rate of 1 SCFM the fluid pass through the empty spaces of the particles without making any fluidization and that’s why a fixed bed were visualized.

The minimum fluidization velocity calculated in section 4.1 was used to estimate the true-value of the gas flow rate at which all the granular material particles were suspended in the stream of the fluid to begin fluidizing. In consequence, the following calculation demonstrate that the flow rate at which minimum fluidization regime occurs is:

$$Q = \ 2.17\,cm \ \ s \quad \frac{\pi * (9.5\,cm)^2}{4}$$

$$Q = 153.81\,\frac{cm^3}{s} \rightarrow 0.326\,scfm$$

As the result shown, the visual observation procedure is an approximate solution because depending on the type of equipment used to observe the fluidization inside the bed chamber and measure the real gas flow rate that pass through the air system the results will vary. Besides, the person who is in charge of the experimental research could have a different criterion of evaluate each regime of fluidization.

5. CONCLUSION AND RECOMMENDATIONS

5.1. CONCLUSION

This study determined and predicted important results of fluidization parameters, which will optimize and improve the design for fluidized bed used in carburizing process for superficial hardness. The following conclusive findings of this experimental research were obtained related to the objectives established in Chapter 1.

Objective 1: Classified the granular material using the Geldart's particles classification.

Conclusion 1: The material was sieve in the mesh no.100, with a particle diameter between $0.149 - 0.297\ mm$, using a mechanical shaker. The classification of the granular material guaranteed its fluidization in the bed chamber and allowed the visual observation for the different regimes that the material presented. Results showed that four fluidization regimes occurred during the variation of the flow rate and there were the fixed bed regime, the minimum fluidization regime, the bubbling fluidization regime and the slugging regime. This classification predict the behavior of the granular material, and it also showed that particles from group A were ideal for fluidizing, and had good properties to work in a cold fluidized bed.

Objective 2: Determine the minimum fluidizing velocity, the maximum fluidizing velocity and the bubbles size for a granular material composed by 90% activated carbon and 10% calcium carbonate.

Conclusion 2: Using mathematical correlations and the visual observation method, the fluidization parameters were estimated and evaluated. The results obtained by these two methods showed some discrepancy that are attributed to the conditions and assumptions considered for each method. They showed the behavior of the granular material at different flow rates and a deep study of each parameter was made. Fluidization was understood and the results of this work will allow to improved pack carburation processes based on the properties of the granular material and the gas used to fluidize the bed.

Objective 3: Visualized the granular material behavior at different fluidizing velocities rates.

Conclusion 3: Using flow rates between 0 – 8 SCFM, four different fluidization regimes were observed among the 20 experiments made in this work. The fluidization regimes were important to understand the behavior of the material when the particles were suspended in an upward-flowing stream of gas in the fluidized bed.

5.2. RECOMMENDATIONS

Future experiments should be performed with a more accurate air system instruments such the pressure regulator and the flow meter, because the higher range of measurement didn’t permit to estimate the true value of the gas flow rates. Moreover, the pressure manometer is very important to have with a lower range to measure the pressure inside the bed chamber because the drop pressure method is a very accurate process to evaluate and estimate the minimum fluidization velocity.

Moreover, future studies should use a different compound of carburizing process since the particles that were used presented too much powder once they were fluidized.

Lastly, in future fluidization experiments, the laboratory should have a better ventilation system that guarantee health conditions to work with the granular material.

6. REFERENCES

Anonymous. (2016). *University of Groningen*. Retrieved from Chapter 2: Introduction of Fluidization: http://www.rug.nl/research/portal/files/9807330/c2.pdf

Barreira, V. (2007, Abril). *Estudio Hidrodinamico de un Lecho Fluidizado*. Retrieved from Universidad Carlos III de Madrid: http://e-archivo.uc3m.es/bitstream/handle/10016/1161/pfc_lecho_fluidizado.pdf?sequence=1

Carrillo, K. (2015, Agosto). Desarrollo del Proceso de Cementacion para Endurecimiento Superficial mediante Empaquetamiento de polvos y fluidizacion. *Tesis Universidad San Francisco de Quito*.

Castellanos, J. P. (2015). Diseño y construcción de un reactor de lecho fluidizado para el estudio de mezcla y segregación de gases y sólidos. . *Tesis Universidad San Francisco de Quito* , 3,15-19,26-29.

Conesa, J. (n.d.). *Reactores de Lecho Fluidizado* . Retrieved from Universidad de Alicante: http://rua.ua.es/dspace/bitstream/10045/15296/6/Tema6_rlf_RUA.pdf

Daizo Kunii, Octave Levenspiel . (1991). *Fluidization Engineering.* USA: Butterworth-Heinemann .

Escudero, D. (2014). *Characterization of the hydrodynamic structure of.* Iowa State University .

Ferrero, L. (2012). *Procesos Termoquimicos de Endurecimiento Superficial*. Retrieved from Universidad Nacional de Lujan: https://cienciamateriales.files.wordpress.com/2012/08/endurecimiento-superficial.pdf

Fogler, S. (2006). *Elements of Chemical Reaction* . Retrieved from http://www.umich.edu/~elements/12chap/html/FluidizedBed.pdf

Hernandez, P. (2009). *Estudio Hidrodinamico de la Fluidizacion de particulas cilindricas* . Retrieved from Instituto Tecnologico de Durango: http://tecno.cruzfierro.com/tesis/01040863-hernandez-mciq-tesis

J. Ruud van Ommen & Naoko Ellis. (2010). *Fluidization .* Retrieved from Univeristy of British Columbia Canada: http://www2.msm.ctw.utwente.nl/sluding/TEACHING/ParticleTechnology/vanOmmen_Fluidization.pdf

Keller, N. K. (2012). *Mixing and segregation in 3D multi-component.* Graduate Theses and Dissertations. Paper 12593: http://lib.dr.iastate.edu/cgi/viewcontent.cgi?article=3600&context=etd.

Levenspiel, O. (1987). *Ingenieria de las Reacciones Quimicas.* Mexico DF: Repla S.A.

Rodriguez, F. D. (2007). *Endurecimiento Superficial del Acero*. Retrieved from Facultad de Estudios Superiores Cautitlan: http://olimpia.cuautitlan2.unam.mx/pagina_ingenieria/mecanica/mat/mat_mec/m6/endurecimiento%20superficial%20del%20acero.pdf

Yang, W.-C. (1999). *Fluidization, Solids Handling and Processing.* Pittsburgh: Noyes Publications.