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DESIGN AND FABRICATION OF FLUIDIZED-BED REACTOR

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Abstract

A fluidized-bed reactor was designed and constructed for practical demonstration of the fluidization of solid particles at different fluid flow rates. The bed of this reactor was sand particles of average size 1800 µm ,weighed 0.6 N and the fluidizing fluidwas air. Alternatively, the fluidizing fluid can be substituted for any given gas by connecting the desired gas cylinder to the blower. The height of the bed was 25 mm on a mesh of 1230 µm. An air blower was designed to supply air from the room to fluidize the bed.The shaftand discharge powers of the blower were18.8kW and its efficiency was 70%. The minimum and maximum operating pressures were 0.1133 and 24.5262 mH_2O and their corresponding velocities were 0.64 and 245.86 m/s respectively.This project was found suitable for undergraduates of Chemical Engineering and related studies for improved knowledge and practical skill required for effective and optimal performance in meeting industrial needs towards improved service delivery.

Keywords: fluidized bed, reactor, demonstration, blower, power.

1.0 Introduction

Fluidized bed reactors have been significantly utilized in chemical processes, in which parameters such as diffusion or heat transfer are the major design parameters. Compared to packed bed, a fluidized bed has notable advantages such as better control of temperature, no hot spot in the bed, uniform catalyst distribution and longer life of the catalyst. Fluidized beds achieve good mixing of the suspended particles and the suspending fluid.

In fluidized bed reactor the solids or catalytic particles are supported by an up flow of fluidizing fluid. This reactor provides easy loading and removing of catalysts (Internet (a)). This is advantageous when the solids bed must be removed and replaced frequently. A high conversion with a large throughput is possible with this type of reactor. Such reactors inherently possess excellent heat transfer and mixing characteristics. The desirability of using fluidized-bed is dependent on achieving good and close to perfect mixing between the solids and the suspension fluid (Idris *et al*, 2007).

Fluidization occurs when small solid particles are suspended in an upward-flowing stream of fluid. The fluid velocity is sufficient to suspend the particles, but not large enough to carry them out of the vessel (Brown and Fogler, 2008). The solid particles swirl around the bed rapidly, creating excellent mixing among them. The material fluidized is always a solid and the fluidizingmedium is either a liquid or a gas. The characteristics and behavior of a fluidized bed are strongly dependent on both the solid and fluid properties.

Because air flows upward through the filter (distributor), the sand in the filter becomes suspended or fluidized in the air column, forming a fluidized bed of sand. If the flow of air is controlled properly, the sand does not flow out of the filter, but remains suspended (Doki, 2011). This happens because the flow of air is just fast enough to keep the sand in suspension. The weight of the sand prevents it from escaping the column. Fluidizedbed filters are self cleaning, and require little or no maintenance.

This fluidized bed unit was designed for the study of the characteristics of flow through beds of solid particles using air as fluid. Low flow rates allow characteristics of a solid bed to be investigated. Increasing flow rates allow the onset of fluidization and the characteristics of a fluidized bed to be investigated.

2.0 Literature Background

Mass of Solid in the Bed

There is a drag force exerted on the solid particles by the flowing fluid, and at low fluid velocities the pressure drop resulting from this drag follows the Ergun equation, (Brown and Fogler, 2008), just as for any other type of packed bed. When the fluid velocity is increased to a certain value however, the total drag on the particles will equal the weight of the bed, and the particles will begin to lift and barely fluidize. This is expressed in equation 1;

$$W_s = \rho_s A_s h(1-\varepsilon) \tag{1}$$

Where, W_s =Mass of solids in the bed,

P_s = Density of solid,

A_s = Cross-sectional area of solid,

h = Height of the bed settled before the particles start to lift, and

ϵ = Void fraction of bed.

The void fraction of bed is expressed as;

$$\varepsilon = 1 - \frac{mass\ of\ \ particles}{\rho_s \times total\ bed\ volume} \tag{2}$$

The macroscopic observables in fluidized beds are the fluid pressure drop (ΔP) needed to cause the fluid to flow through the bed of solids, the fluid velocity (u), and the density of solids (ρ_s). The Ergun equation (Idris *et al*, 2007) is represented as in equation 2;

$$\frac{\Delta P}{h} = 150\frac{(1-\varepsilon)^2}{\varepsilon^3}\frac{\mu u}{d_p^2} + 1.75\frac{(1-\varepsilon)}{\varepsilon^3}\frac{u\rho_f}{d_p}$$

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Where, ΔP = pressure drop

h = Height of the bed,

μ = fluid viscosity,

ρ_f = Fluid density,

ϵ = Void fraction of bed,

u = fluid velocity, and

d_p = Particle diameter.

The equation for turbulent flow is different from streamline situation. The particles in the bed will remain in a parked bed as the gravitational forces holding the solid particles down are greater than the force exerted by the fluid flowing up through the bed particles. At the point where the two forces become equal, the solid particles begin to move up. The force balance describes this condition known as incipient fluidization (Idris *et al*, 2007 & Brown and Fogler, 2008) is given in equation 4;

$$\frac{\Delta P}{h} = (\rho_s - \rho_f)(1-\varepsilon)g$$

4

The minimum fluidized velocity, u_{mf} in terms of parameters for the fluid, solid and bed is expressed (Missen *et al*, 1999) as in equation 5;

$$u_{mf}^2 + \frac{150(1-\varepsilon_{em})\mu_f}{1.75\rho_f d_p^!}u_{mf} - \frac{g(\rho_p - \rho_f)\varepsilon_{mf}^3 d_p^!}{1.75\rho_f} = 0$$

5

For relative small particles and small Reynolds number the minimum fluidized velocity (u_{mf}) is expressed as in equation 6;

$$u_{mf} = \frac{8\left(\rho_p - \rho_f\right)\left(d_p^1\right)^2}{150\left(1-\varepsilon_{mf}\right)/\varepsilon_{mf}^3}$$

6

Equation 7 gives the minimum fluidized velocity (u_{mf}) for relative large particles, large Reynolds number;

$$u_{mf} = \left[\frac{g\left(\rho_p - \rho_f\right)\varepsilon_{mf}^3 d_p^!}{1.75\rho_f}\right]^{1/2}$$

7

Terminal Velocity, u_t

The solid particles are entrained when the upward velocity of fluid is sufficiently high and thus they are carried up with the fluid. At this point elutriation occurs. This velocity is called elutriation velocity. *Elutriation is the selective removal of solid particles by entrainment on the basis of size* (Missen *et al*, 1999). The minimum elutriation velocity for particles of a given size is the velocity at incipient entrainment, and is assumed to be equal to the terminal velocity, u_t. The terminal velocity for spherical particles at small Re is expressed (Missen *et al*, 1999) in equation 8 as;

$$u_t = \frac{g\left(\rho_p - \rho_f\right)d_p^2}{18\mu_f}$$

8

Proper fluidization occurs at a velocity called actual fluidized velocity v_f (Hartog et al, 2008 and Missen *et al*,

1999) the relationship between the minimum fluidized velocity u_{mf} and terminal velocity u_t is given in equation 9.

$$u_{mf} \lhd u_f \lhd u_t \qquad 9$$

If the gas velocity is increased to a sufficiently high value, however, the drag on an individual particle will surpass the gravitational force on the particle, and the particle will be entrained in a gas and carried out of the bed. The point at which the drag on an individual particle is about to exceed the gravitational force exerted on it is called the *maximum fluidization velocity*.

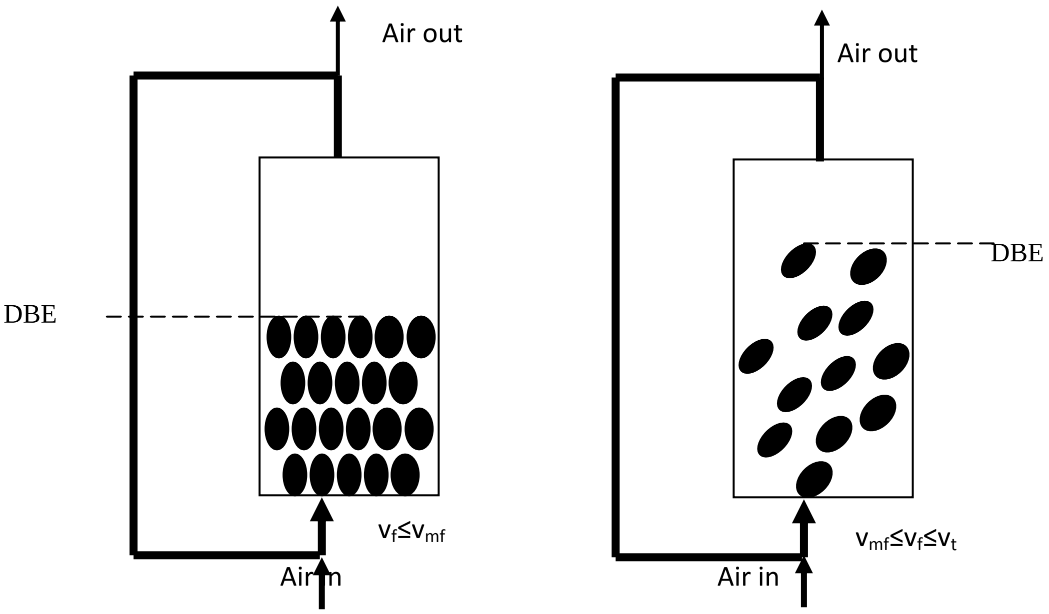

Figure 2.1: Conceptual Fluidized Reactor Containing Uniform Particles with Degree of Bed Expansion (DBE) as Related to flow velocity v_f.

The fluidized velocity (u_f) expressed by Kozeny-Carmen equation is as in equation 10

$$u_f = \frac{\left(\rho_p - \rho_f\right) g d_p^2}{150\mu} \frac{\varepsilon^3}{1-\varepsilon} \qquad 10$$

3.0 Materials and Method

3.1 Materials of Construction

3.1.1 The Reactor

The reactor was a glass tube of 1m long and 40 mm diameter obtained from the store of theDepartment of Chemical Engineering, Ahmadu Bello University(A.B.U), Zaria, Nigeria, under the authority of the Head of Department. Sand particles were collected in front of Chemical Engineering Department. The sand particles were sieved to the desired particle size (in accordance with BS 1377 (1990)) in the Department of Building; Faculty of Environmental Design of A.B.U., Zaria. The lower part of the reactor was fitted with a mesh of 1.23mm (1230μm) at the base and also at the top to prevent (the undesired escape of the solid particles from the reactor). The bed of the reactor was filled with sand particles of weight 0.6N and average size of 1800μm to a height of 25mm. Also, theU-tube differential manometer made up of plastic (transparent) tube was filled with water for the experiment.

3.2 Design of the Bed

The density of the sand was determined (in accordance with BS 1377 (1990)), and it was found to be 2.6129g/cm^3. Choosing the height of the bed to be 25 mm for a tube of 40 mm diameter, the bed void from equation (2) was;

$$\varepsilon = 1 - \frac{60}{2.6129 \times \pi \times 4^2 \times 2.5/4} = 0.269$$

The pressure drop ΔP was calculated from equation (4)

$$\Delta P = 0.025 \times 9.81(2612.9 - 1.25)(1 - 0.269) = 468.031 N/m^2$$

Or 4.77cm H_2O

Minimum fluidized velocity was calculated from equation (7)

$$u_{mf} = \left[\frac{9.81(2612.9 - 1.25) \times 0.269^3 \times 1.8 \times 10^{-3}}{1.75 \times 1.25}\right]^{1/2} = 0.64 m/s$$

Fluidized velocity wascalculated from equation (10)

$$u_f = \frac{(2612.9 - 1.25) \times 9.81 \times (1.8 \times 10^{-3})^2 \times 0.269^3}{150 \times 18.75 \times 10^{-6} \times (1 - 0.269)} = 0.79 m/s$$

Terminal velocity was calculated from equation (8)

$$u_t = \frac{9.81 \times (2612.9 - 1.25) \times (1.8 \times 10^{-3})^2}{18 \times 18.75 \times 10^{-6}} = 245.86 m/s$$

The cross-sectional area of the bed was thus,

$$A = \frac{\pi d^2}{4} = \pi \times 16 \times 10^{-4} / 4 = 1.257 \times 10^{-3} m^2$$

Hence, the flow rate at various velocities wascalculated as;

$$\phi = A \times u \; .$$

The flow rate at minimum velocity is;

$$\phi = 1.257 \times 10^{-3} \times 0.64 = 8.04 \times 10^{-4} m^3/s$$

The flow rate at fluidized velocity is;

$$\phi = 1.257 \times 10^{-3} \times 0.79 = 9.93 \times 10^{-4} m^3/s$$

The flow rate at terminal velocity is;

$$\phi = 1.257 \times 10^{-3} \times 245.86 = 0.309 m^3/s$$

The minimum and maximum power requirements of the bed were calculated from equations 11 and 12 respectively below.

$$Q_{\min} = \Delta P_{\min} \times \phi_{\min}$$

11

$$Q_{\max} = \Delta P_{\max} \times \phi_{\max}$$

Using equation (3) the pressure drop at minimum fluidized, fluidized velocity and terminal velocity were calculated and tabulated in table 1 below;

Table 1: Summary of the Design Results

Velocity (m/s)	ΔP (mH_2O)	ΔP N/m^2	ϕ (m^3/s)	Power (W)
0.64	0.1133	1111.505	0.000804	8.94
0.79	0.1399	1372.014	0.000993	13.62
245.86	4.3526	42691.66	0.309	13191.72

From the table 1 above, the power required for maximum fluidization was 13.2kW. It is therefore the discharge power of the blower.

3.3 Blower Design

The blower head was calculated from the discharge power as;

$$P_d = \rho g \phi H$$

$$\Rightarrow H = \frac{P}{\rho g \phi} = \frac{13191.72}{1.3 \times 9.81 \times 0.309} = 3347.58m$$

This is equivalent to 4.35m (H_2O)

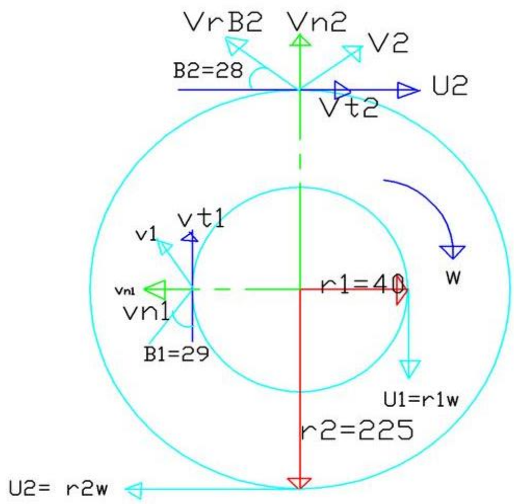

Figure 2: Velocity vector diagram of impeller wheel of the blower

According Adekunle *et al* (2008), the volume flow rate can be expressed as;

$$\phi = 2\pi r_1 b_1 v_{n1}$$

Where, ϕ is volume flow rate, r_1 is radius of suction eye, b_1 is the blade width and $v_{n1}$is speed of the suction eye along the radius. Hence,

$$\nu_{n1}=\frac{\phi}{2\times\pi\times r_1\times b_1}=\frac{0.309}{2\times\pi\times0.06\times0.04}=20.49m/s$$

But $\nu_{n1} = U_1 \tan\beta_1$

Hence,

$$U_1=\frac{\nu_{n1}}{\tan\beta_1}=\frac{20.49}{\tan 29}=36.96m/s$$

$$N=\frac{36.96\times60}{0.06\times2\times\pi}=5882.37rpm$$

$$U_2=r_2\omega=\frac{2\times\pi N}{60}\times0.225=138.62m/s$$

$$V_{n2}=\frac{\phi}{2\times\pi\times r_2\times b_2}=\frac{0.309}{2\times\pi\times0.225\times0.032}=6.83m/s$$

The impeller discharge velocity, V_2,

$$V_2=\sqrt{U_2^2+V_{n2}^2}=\sqrt{138.63^2+6.83^2}=138.80m/s$$

Assuming that the fluid enters the impeller with purely radial absolute velocity, (Cheng-Kang and Mu-En, 2009) ν_{t1} = 0.

The increase in head becomes

$$H=\frac{U_2\times V_{t2}}{g}$$

$$\Rightarrow V_{t2}=\frac{Hg}{U_2}=\frac{3347.58\times9.81}{138.63}=244.81m/s$$

$$V_{t2}=U_2-V_{n2}Cot\beta_2$$

$$\Rightarrow\cot\beta_2=\frac{V_{t2}}{U_2-V_{n2}}=\frac{244.81}{138.63-6.83}=1.8574$$

$$\beta_2=28^0$$

The blower discharge power was;

Taking the efficiency of this blower to be 70%, according to Robert (2002) the new-generation blowers typically deliverwell in excess of 70 percent efficiency, the input or shaft power is thus;

$$P_S=\frac{P_d}{\eta}=\frac{13191.72}{0.7}=18845.31W$$

Therefore, the power of the electric motor requires for this duty is 18.85kW.

Table 2: Blower specifications

Name	Value	Unit
Number of blade	5	
Blade diameter	450	mm

Blade width, w	40	mm
In let velocity, U_1	36.96	m/s
Discharge velocity, U_2	138.63	m/s
Blower head	3 347.58	m
Rotational speed	5882.37	rpm
Discharge Power, P_d	13 191.72	W
Shaft power, P_s	18 845.31	W
Efficiency, η	70	%

The workings drawings of blower and its impeller assemble are depicted in the figure 3 and figure 4 respectively. Also the blower/ electric motor couple and impeller blades arrangement are shown in figure 5 and figure 6 respectively.

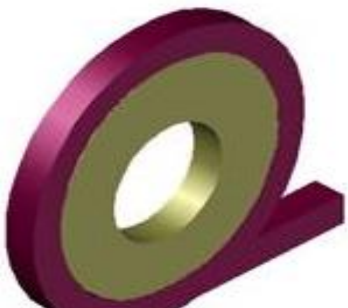

Figure 3: Isometric view of the blower

Figure 4: Close impeller assembles

Figure 5: Blower/ electric motor couple

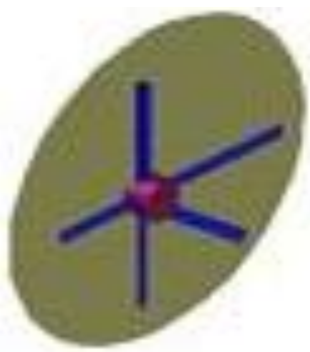

Figure 6: Impeller

3.4 Plant Layout

The major component of this reactor were 1 m glass tube, a blower, an electric motor of 1.5kW, a manometer, control board and the metal frame. The whole setup was 1.2 x 1.4 x 0. 6 m. The front and back views of the plant are shown in plates 1 and 2 below.

Plate 1: Front view of the fluidized bed reactor

Plate 2: Back view of the fluidized bed reactor.

3.5 Conclusion

A fluidized reactor for practical demonstration was successfully designed and fabricated and also tested. The pressure drops relative to flow of air was studied and found satisfactorily. This project was found suitable for undergraduates of Chemical Engineering studies. The minimum and maximum fluidized velocities were 0.64 and 245.86 m/s and the corresponding pressure drops were 0.11 and 43.53mH_2O respectively. The blower rotational speed was 5882 rpm and its efficiency was found to 70%. The blower head was 3347.58 m indicating that it can blow gas to this height.

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