Btech Thesis on

STUDY OF FLOW OF GRANULAR SOLIDS THROUGH HORIZONTAL ORIFICES

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Bachelor of Technology

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CERTIFICATE

This is to certify that the thesis entitled "**Study of Flow of Granular Solids through Horizontal Orifices**" submitted by **Satarupa Dhir** (109CH00071) in partial fulfillment of the requirements for the award of degree of Bachelor of Technology in Chemical Engineering at National Institute of Technology, Rourkela is an authentic work carried out by her under my supervision and guidance.

To best of knowledge, the matter embodied in this thesis has not been submitted to any other university or institute for the award of any degree.

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ABSTRACT

A granular material is a conglomeration of discrete macroscopic particles. They have properties different from those commonly associated with solids, liquid and gases. The science of granular media has a long history with much engineering literature devoted to understanding how to deal with these materials. Many of our industries rely on transporting and storing granular materials. These include the pharmaceutical industries that rely on the processing of various powders and pills, agricultural and the food processing industry where various seeds, grains, and foodstuffs are transported and manipulated. The construction-based industries are also included. Flow rate of granular solids through various sizes and shapes of orifice is necessary so as to properly size the opening for flow control during transfer of materials. The flow rate is key to calculate the kinematic parameters and velocity profile of the solids in the column. In the past most of the work upon the flow rates of granular solids have been the by-product of research into pressure distribution in hoppers or bins. In this study, the variable of importance influencing the mass rate like orifice diameter, particle diameter, particle density and angle of repose are studied and an empirical equation is suggested relating them all.

Keywords: Horizontal orifice, Granular materials, Mass Flow rate, Empirical equations.

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NOMENCLATURE

ρ_p , ρ_s = Particle Density.

D_0= Orifice Diameter.

μ_s= Static Friction factor.

α= Angle of Repose.

Θ= Inclination angle of the orifice plate.

W= Mass flow rate

A= Area of the orifice.

D_h= Hydraulic diameter.

d= Particle diameter.

ρ_B= Bulk Density.

λ= Shape factor.

CHAPTER 1

INTRODUCTION

1. INTRODUCTION

1.1 GRANULAR MATERIALS

Granular materials are conglomeration of discrete macroscopic particles. They are characterized by two important aspects[1]:-

- Loss of energy whenever some amount of interaction occurs (mostly due to friction) during collision.
- Ordinary temperature plays no role.

Granular materials are present everywhere and second most manipulated material in the industry. They exhibit range of complex pattern forming behaviors when excited.

1.2 GRANULAR SOLIDS

When the average energy of the individual grains is low and grains are stationary relative to each other, then they act like solid. In general granular solids are not distributed uniformly.

1.3 GRANULAR LIQUIDS

When the energy is fed into the granular system such as by shaking, the grains are not in constant contact with each other. They are said to be in fluid like state. When freely flowing, granular materials have flow characteristics resembling Newtonian fluids. Bulk flow characteristics of granular materials differ from homogenous fluid in several ways like:-

- Granular fluid tends to clog when forced through constrictions.
- It is impossible to achieve turbulence in granular materials.
- They can support small shear stresses indefinitely.
- Granular materials are often inhomogeneous and anisotropic.
- They exhibit avalanches.
- When held in tall silos no height dependent pressure bed occurs as it does in normal fluid. The pressure at the base of the container does not increase indefinitely as the height increases, instead it reaches a maximum value independent of height.

1.4 GRANULAR GASES

When the interaction between grains becomes highly infrequent then the materials are said to be in gaseous state. In this state the materials would tend to cluster and clamp due to the dissipative nature of collision.

Some examples of granular materials are nuts, coal, sand mustard, saw flakes, glass beads, ball bearing, fertilizers, rice and other grains. Powders are special class of granular material due to their small particle size which makes them more cohesive and suspended in gas.

Study of flow of granular materials is important in many industries as they rely on storing and transportation. For example: - pharmaceutical industry depends on processing of powders and pills, agriculture and food industries require storage and transportation of seeds, grains and foodstuffs.

1.5 OBJECTIVE

There has been little systematic work published in literature upon the flow characteristics of granular solids flowing through hoppers or flat bins. Due to lack of any reliable formula for predicting the flow rate of granular solids the design of bins is somewhat empirical in nature. It is the objective of this paper to investigate the flow of granular materials through various orifices from vertical columns to find the effect on variables such as bulk density, head, orifice diameter, particle diameter and container diameter on the flow rates.

CHAPTER 2

LITERATURE REVIEW

2. LITERATURE REVIEW

2.1 FLOW THROUGH CIRCULAR ORIFICE[2]

Effect of following variables was made:-

- Orifice diameter.
- Particle diameter.
- Particle density.
- Angle of repose (both static and kinetic).
- Bed height.
- Void fraction.
- Angle of inclination of orifice.

2.1.1 EXPERIMENTAL SETUP:-

Material was poured into vertical glass column and was allowed to flow downward through a circular orifice in a 1/16 inch plate (1.58 mm). The orifice was horizontal and centered at the bottom. Column diameter from 1.76 inch to 8.81 inch was used. The particle diameter was varied from 0.03inch to 0.2 inch. The diameter was determined by the average of direct measurement for large particles and by arithmetic average screen mesh size of fraction of smaller particles. Particle density was varied from 7.34lb/ft^3 to 670lb/ft^3. Static bed void fraction was calculated from particle density and bulk density values. Angle of repose was calculated in a special apparatus. It consist of a rotating drum 1ft in diameter and 8 inch long with axis fixed in a horizontal position and having a front face of transparent Lucite plastic through which various angles of repose could be observed. The curved surface was roughened and drum was rotated at about 5 to 6 rpm. The maximum angle of repose attainable by solid surface before moving or cascading downward was recorded as static angle of repose

Equation used was:-

$$W = \frac{\rho_{p} \; {D_0}^{2.93}}{(6.288\mu_s + 23.16)(D_p + 1.889) - 44.90} \qquad (1)$$

Orifice can also be inclined at an angle θ with the horizontal. Then the modified flow rate can be defined as:-

$$W_\theta = W_0 \frac{\cos\alpha+\cos\theta}{\cos\alpha+1} \quad (2)$$

Fowler and Glastonbury[3] also suggested an empirical equation relating all the variables with flow rate.

$$\frac{W}{\rho_s\ A\sqrt{2gD_h}} = a\left(\frac{\rho_s}{\rho_b}\right)^b \left(\frac{D_h}{d_s}\right)^c \left(\frac{D_c}{d_s}\right)^d \left(\frac{H}{d_s}\right)^e \quad (3)$$

Where

$d_s = \lambda d$

and λ i.e. shape factor is calculated by LEA and NURSE apparatus.

They reduced the empirical equation to a less tedious final equation:-

$$\frac{W}{\rho_B\ A\sqrt{2gD_h}} = 0.236\left(\frac{D_h}{d_s}\right)^{0.185} \quad (4)$$

The more popular equation was suggested by Beverloo[4]. Materials used by him included linseed, rapeseed, turnip and sand. Number of characteristic properties such as bulk density and angle of repose were determined. Particle size distribution of seeds and sand was found by screening method. The flow rate was determined by catching material during definite time after the flow had become stationary. Then the material caught was weighed. The experimental results can be compared to the theoretical one:-

$$W = 35\rho_B\sqrt{g}\,(D_0 - 1.4d)^{2.5} \quad (5)$$

The mass flow rate W is expressed in gm/min.From the above experiments it can be inferred that the height of packing has no influence on the flow rate. The diameter of the cylinder also doesn’t affect the flow rate. Particle size has a slight influence on the flow, but its affect decreases as the ratio of orifice diameter to particle size increases. When the ratio is more than 20 then the influence is negligible. It is seen that the flow rate decreases from circular, square, rectangular to triangular shaped orifice diameter.

It is now well established that a power law relationship holds between the rate of flow of the material and the size of the orifice. A general form of this relationship is:-

$$W = A\,(D_0)^n \quad (6)$$

On the basis of dimensional analysis carried out by several investigators “n” should have value of 2.5. Moreover if it is assumed that the material is completely loose packed as it emerges from the orifice, then by analogy with the fluid case and by application of Bernouilli's theorem, "n" should also have a value of about 2.5. The values of "n" can be plotted by varying Log W with Log D_0. However, we find exponents of D_0 greater than 2.5, particularly with larger d's (particle diameter). This might be explained by assuming that along the margin of the orifice a zone is useless or less fit for use for the flow. The size of that zone is proportional to d, so that the equation $W = \rho_B \sqrt{g}\,(D_0 - k\,d)^{2.5}$ may be valid. In this equation "k" is a dimensionless constant. By plotting D_0 against $W^{0.4}$ we found the following values for k.

Tab 1:- Values of k for different materials

linseed k = 1.5	spinach k = 1.4
Swede k = 1.5	kale k = 1.4
sand k = 2.9	rapeseed k = 1.4
watercress k = 1.3	turnip k = 1.4

For all the seed samples examined it can be therefore assumed that the average value of "k" to be 1.4.

The variations in "k" are probably related to the surface properties, but no correlation with the angle of repose could be established. The equation $W = 35\rho_B\sqrt{g}\,(D_0 - 1.4d)^{2.5}$ can be used for all seed samples for circular orifices. Calculations with this equation show for all the seeds within the scope of investigations deviations of about 5 per cent.

It follows that the equation

$$W = 45\rho_B A'\sqrt{gD'_h} \qquad (7)$$

may be applied for orifices of various shapes. Using the effective hydraulic diameter D'_h so that

$$D'_h = D_h - 1.4d \qquad (8)$$

And the effective orifice area A', the equation shows a smaller deviation value for various materials.

2.1.2 CRITICAL FACTORS

The flow is affected by the ratios of particle, orifice and tube diameters but these can be eliminated if one ensures that the orifice diameter is at least 6 times the particle diameter, the tube diameter is at least the 4/3 power of the orifice diameter and the head of the material is always greater than twice the tube diameter[5][6]. Voidage effects, although known to be small were minimized by filling the tube always from the same height. If the orifice is smaller in size, the beverloo equation fails and jamming can occur. The flow stops due to the formation of an arch spanning over the opening. This arch is called an *avalanche*. From the size of the avalanche and its duration the mean flow can be determined. A formula has been proposed to discuss the flow rate while jamming:-

$$W_b = C'(1 - 0.5e^{-b(R-1)})(R-1)^{2.5} \qquad (9)$$

Where,

R is the ratio of diameter of the orifice outlet and the diameter of the beads/ material used.

2.2 FLOW PATTERNS [7][8][9]

In most situations where granular materials are stored in bins, the material is removed from bins through an opening in the center of the bottom. If the material is free flowing, it usually flows from the bin in one of the three types of pattern shown:-

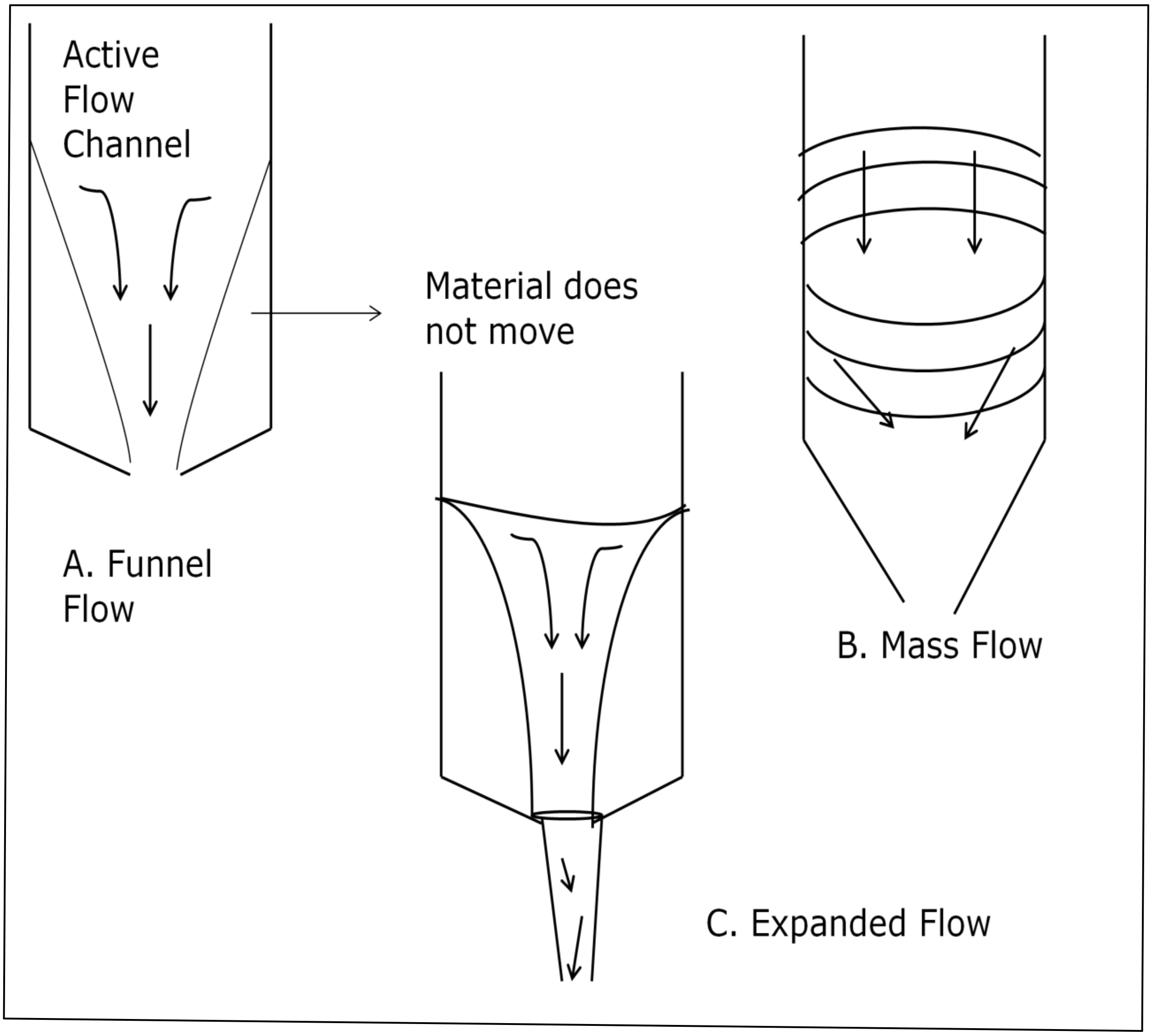

Fig 1:- Flow patterns of granular solids.

2.2.1 FUNNEL FLOW

It occurs in bins with flat bottoms or bins with slopping bottoms in which the angle which the bottom of the bin makes with the vertical is less than the critical angle termed as hopper angle. Here the material first flows from a center “core” which is approximately the size of the opening at the bottom of the bin and which like a funnel slowly expands in diameter with height above the opening. A large ring of material is supported by the floor and remains stagnant. As flow proceeds material from the top surface flows into the funnel of flowing particles. The major advantages are that it is simple in design and easy to build. Construction cost is low. When cohesive materials such as ground animal feeds or fine powders are placed in this type of bin arching may occur and material will flow erratically from the bin.

2.2.2 MASS FLOW

All of the materials flow towards exit at the same time and ideally at the same rate. This type of flow is well suited for processing facilities where additional material is being periodically added to the top of the bin while material is being withdrawn from the bottom. This type of bin is used for storage of animal feeds at livestock facilities. The flow is uniform rather than erratic. Furthermore, the material can act as gas seal because the air entrapped between the particles moves downwards with the material. The major disadvantage is that, for a given capacity the bin must be higher to accommodate the slopping bottom. Beam and columns must be used to support such structures.

2.2.3 EXPANDED FLOW

By constructing the bottom of the bin with two regions having different slopes, mass flow is achieved in a larger portion of the bin and the size of the stagnant region is decreased. This expands the active flow region and permits a smaller discharge orifice.

CHAPTER 3

EXPERIMENTAL SETUP AND PROCEDURE

3. EXPERIMENTAL SETUP AND PROCEDURE

3.1 APPARATUS DESIGN

Two flat bottomed cylinders made up of Perspex sheet, of different height and internal diameter 9.5 cm and 2.5 cm were used. Thickness of the cylinder was about 3mm. Four orifice plates with circular orifices for each cylinder were designed. Material of construction for these plates include 2mm GI steel sheet. For cylinder of diameter 9.5cm, orifice diameters used were 1.1cm, 1.2cm, 1.3cm, 1.4cm and for cylinder of diameter 2.5cm, orifice diameters used were 1.1cm, 1.2cm, 1.3cm and 1.4cm. The cylinders and orifice plates used in the given study are shown below:-

a)

b)

c)

Fig 2:- Experimental setup in the Material Handling lab. a), b)- Column used, c) Orifice Plates

3.2 MATERIAL USED AND PROPERTIES

Both regular and irregular shaped materials were used to the study the flow rate in the flat bottomed cylinders. Mono-dispersed circular glass beads, dry mustard seeds and aluminium balls of specific size were used as regular granular material whereas sand and dolomite (crushed and sized in ball mill) were used as irregular materials. The properties of the materials studied are listed in the table 2.

3.2.1 DETERMINATION OF MATERIAL SIZE

The particle sizes were determined in the standard sieve shaker by sieve analysis and ISS tables were used.

3.2.2 DETERMINATION OF ANGLE OF REPOSE

The material was poured onto the center of the pan. The heap was not disturbed for a while till the movement of particles became stationary. The height and the perimeter of the base were noted with the help of thread.

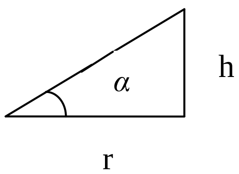

Fig 3:- Measurement of angle of repose[10]

$$\text{Angle of repose } \alpha = \tan\frac{h}{r} \qquad (10)$$

3.2.3 DETERMINATION OF BULK DENSITY

The material is poured from a fixed height to completely occupy 100ml in a measuring cylinder. The amount collected was weighed. The amount collected per unit volume occupied gives the bulk density of the material. It is different from the true density due to the void present between the granular particles.

Tab 2:- Properties of various regular and irregular materials.

Material used	Average dia(cm)	Bulk density (gm/cc)	Angle of repose(^{0})
Glass beads	0.2	1.54	23
Mustard	0.14	0.65	25-28
Al- Balls	0.14	1.59	22-30
Sand	0.06	1.21	31.7
Dolomite	0.1	1.21	35-40

3.3 PROCEDURE

The orifice plates were fixed to the flat bottom columns with the help of flanges. The column was placed on a framework with a height from the ground and a pan underneath the orifice. The material was poured from a fixed height to avoid irregular flow. The bed height was varied from 30cm to 10cm in the three different columns. After that the orifice was unplugged and the time was noted till all flow stops. The mass of the sample collected was weighed and thus mass flow rate was calculated. This procedure was repeated three times for a particular height in each column with a fixed orifice plate. Then the column height was varied along with the different orifice plates and readings were noted.

CHAPTER 4

RESULTS AND DISCUSSION

4. RESULTS AND DISCUSSION

4.1 INFLUENCE OF COLUMN HEAD ON THE FLOW RATE

Tab 3:- Influence of column head on flow rate of glass beads.

Orifice Dia(cm)	Mass flow rate of Glass beads (g/min)					
	H=30cm		H=20cm		H=10cm	
	D=2.5cm	D=9.5cm	D=2.5cm	D=9.5cm	D=2.5cm	D=9.5cm
1.1	811	----	783	----	702	----
1.2	1018	1001	955	988	996	947
1.3	1390	1285	1289	1.392	1190	1070
1.4	1419	2037	1337	1792	1304	1616

Tab 4:- Influence of column head on flow rate of mustard seeds.

Orifice Dia(cm)	Mass flow rate of Mustard (g/min)					
	H=30cm		H=20cm		H=10cm	
	D=2.5cm	D=9.5cm	D=2.5cm	D=9.5cm	D=2.5cm	D=9.5cm
1.1	443	334	424	364	412	345
1.2	586	623	591	665	581	568
1.3	737	681	662	719	622	620
1.4	847	1102	795	934	774	891

Tab 5:- Influence of column head on flow rate of aluminium balls.

Orifice Dia(cm)	Mass flow rate of Aluminium balls (g/min)					
	H=30cm		H=20cm		H=10cm	
	D=2.5cm	D=9.5cm	D=2.5cm	D=9.5cm	D=2.5cm	D=9.5cm
1.1	983	858	969	700	789	785
1.2	1165	1391	1159	1512	1215	1223
1.3	1561	1501	1681	1645	1385	1275
1.4	1836	2389	1780	2077	1395	1836

Tab 6:- Influence of column head on flow rate of sand.

Orifice Dia(cm)	Mass flow rate of Sand(g/min)					
	H=30cm		H=20cm		H=10cm	
	D=2.5cm	D=9.5cm	D=2.5cm	D=9.5cm	D=2.5cm	D=9.5cm
1.1	1172	886	1160	1079	1054	861
1.2	1366	1881	1354	1635	1302	1507
1.3	1939	2105	1768	1794	1500	1676
1.4	2126	2593	2069	2514	1870	2331

Tab 7:- Influence of column head on flow rate of dolomite.

Orifice Dia(cm)	Mass flow rate of Dolomite (g/min)					
	H=30cm		H=20cm		H=10cm	
	D=2.5cm	D=9.5cm	D=2.5cm	D=9.5cm	D=2.5cm	D=9.5cm
1.1	793	----	754	----	742	----

1.2	934	1187	930	1281	791	1064
1.3	1331	1269	1159	1346	1244	1261
1.4	1535	2049	1444	1759	1293	1704

4.2 INFLUENCE OF THE DIAMETER OF THE COLUMN ON THE FLOW RATE

Tab 8:- Influence of column diameter on flow rate of granular materials.

Orifice Dia (cm)	Mass flow rate (g/min)									
	Glass Beads		Mustard		Al- Balls		Sand		Dolomite	
	D=2.5 cm	D=9.5 cm	D=2.5 cm	D= 9.5 cm	D=2.5 cm	D= 9.5 cm	D= 2.5 cm	D=9.5 cm	D= 2.5 cm	D=9.5 cm
1.1	811	-----	426	348	914	781	1128	942	764	----
1.2	989	979	586	619	1179	1375	1341	1674	885	1177
1.3	1289	1249	674	673	1542	1474	1736	1858	1245	1292
1.4	1353	1815	805	976	1670	2100	2022	2479	1424	1837

Based on the observed values, graph was plotted for Mass flow rate vs. diameter of the orifice of the granular materials. The nature of graph showed a nonlinear rise. However the diameter of the column has no influence on the mass flow rate of the regular and irregular materials as the flow rates for the same orifice diameter remains nearly same for columns of diameter 2.5cm and 9.5cm.

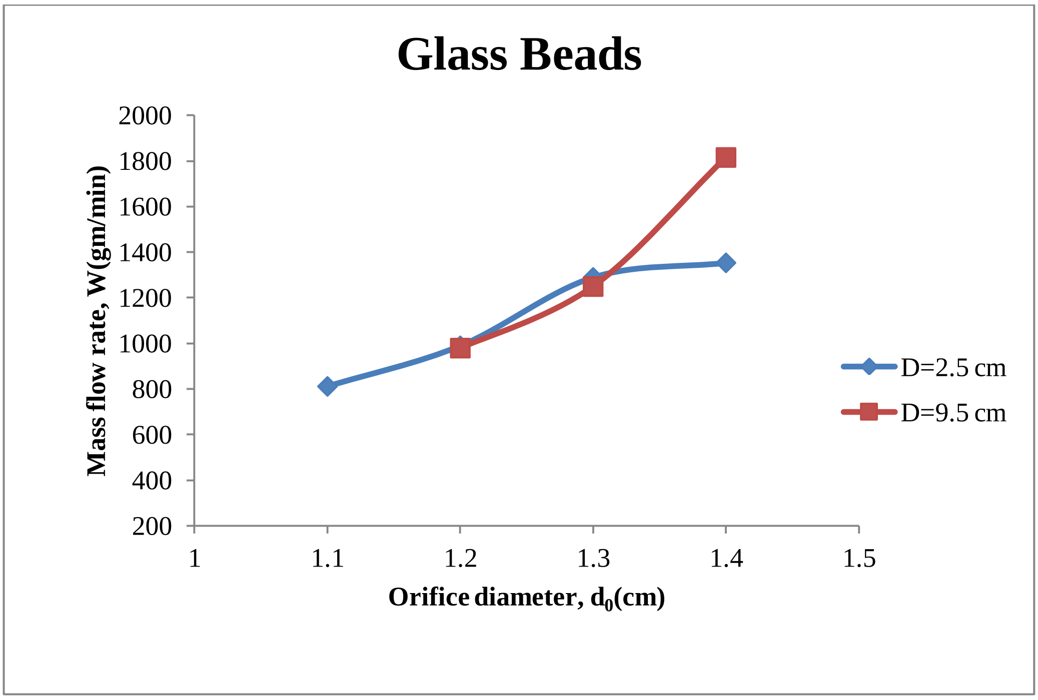

Fig 4:- Mass flow rate (gm/min) vs orifice diameter (cm) for glass beads.

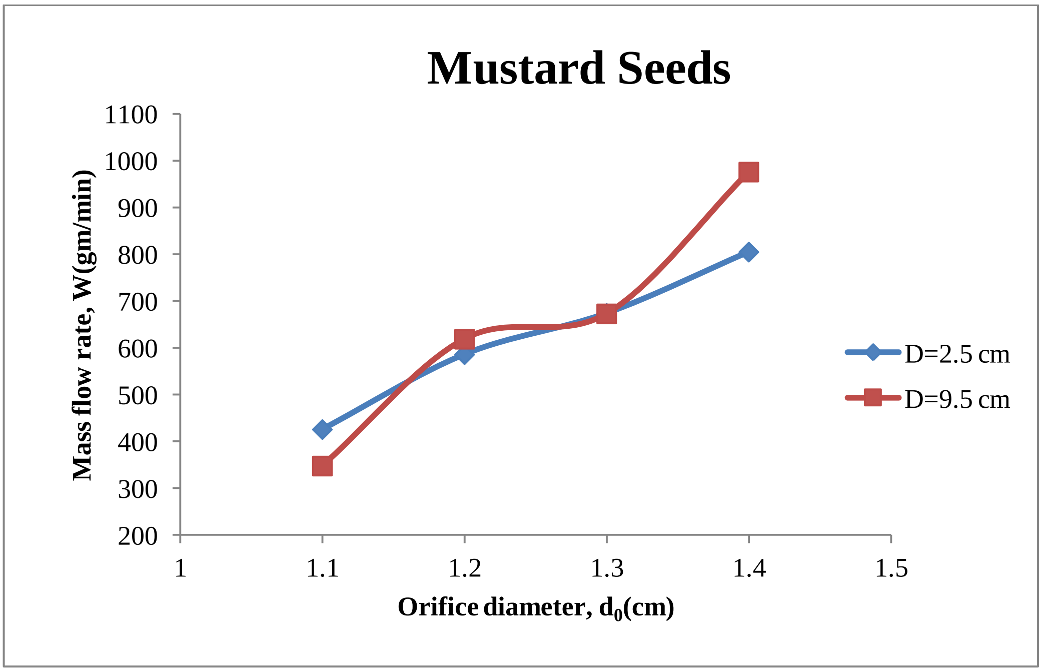

Fig 5:- Mass flow rate (gm/min) vs orifice diameter (cm) for mustard seeds.

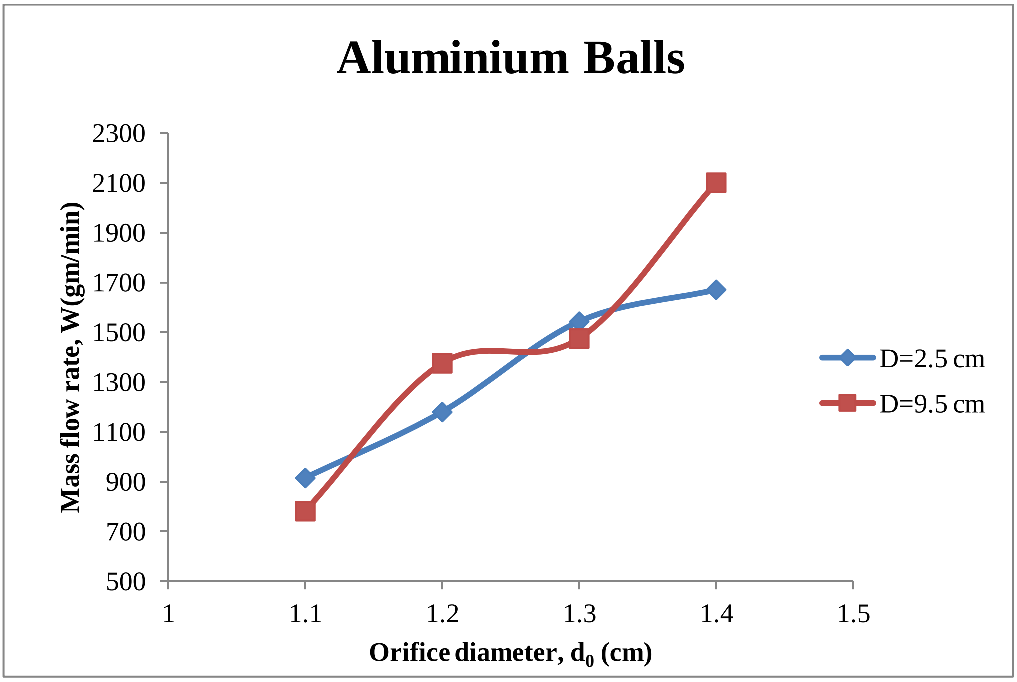

Fig 6:- Mass flow rate (gm/min) vs orifice diameter (cm) for aluminium balls.

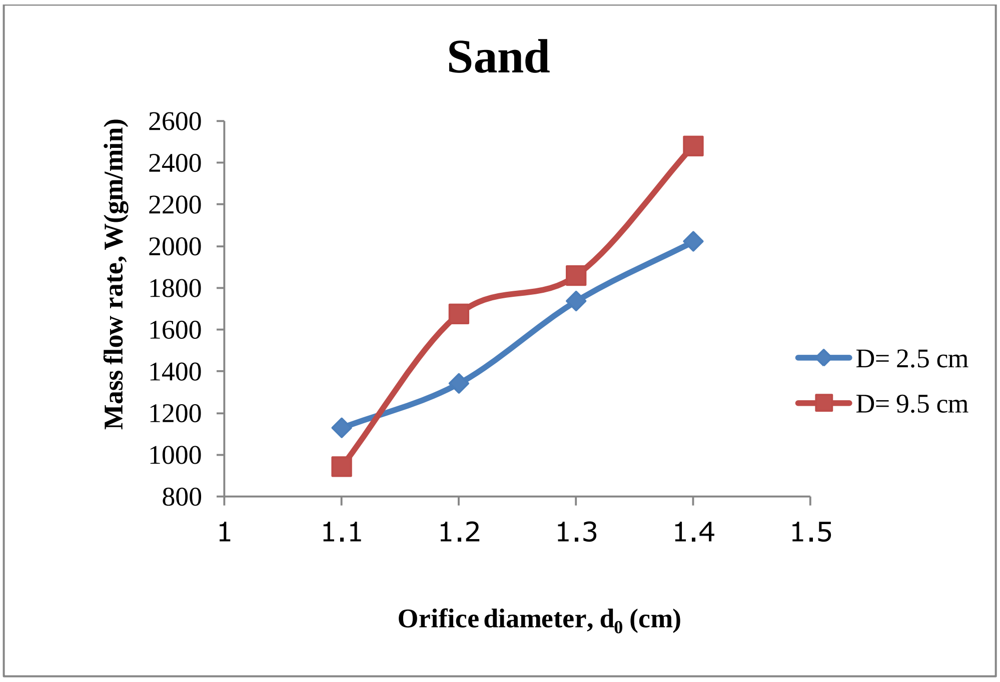

Fig 7:- Mass flow rate (gm/min) vs orifice diameter (cm) for sand.

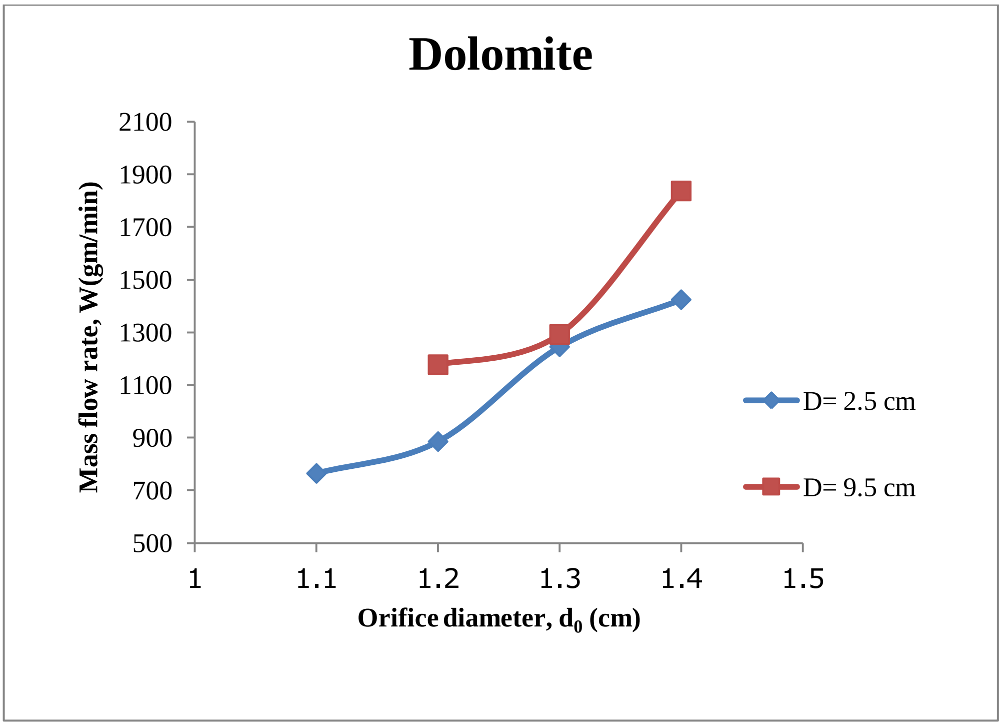

Fig 8:- Mass flow rate (gm/min) vs orifice diameter (cm) for dolomite.

4.3 DIMENSIONAL ANALYSIS

From Literature it has been observed that the mass flow rate W of a free flowing granular material through a circular orifice of diameter d_0 in the base of the flat bottomed flat bottomed column might reasonably be expected to depend on the depth of material in flat bottomed column H, the diameter of the flat bottomed column D, particle diameter d, the gravitational acceleration g, the bulk density if the material ρ_B as shown below:

$W= f(d_0, d, H, D, g, \rho_B)$

From the experiments carried out it has been observed that neither the flat bottomed column diameter D nor the quantity of materials in the column as typified by the height H has any significant effect on the flow rate. Moreover since $d<<d_0$ the effect of particles is slight. This can be shown below:

$W \neq f(D, H, d)$

Therefore, $W \propto d_0^a g^b \rho_B^c$

$W= A d_0^a g^b \rho_B^c$, where A is a constant of proportionality.

LHS: $W= M^1T^{-1}$ RHS: $d_0^a g^b \rho_B^c = M^c L^{a+b-3c}T^{-2b}$

After comparison of the coefficients we observe that:-c=1, b=0.5, a=2.5

Therefore the Flow rate could roughly be expressed as:

$$W= A\rho_B g^{0.5} d_0^{2.5} \quad (11)$$

However it has been observed that a margin along the orifice diameter is useless and is proportional to particle diameter. The effective orifice diameter can be defined as:-

$$d' = d_0 - kd$$

Therefore,

$$W = A\rho_B\, g^{0.5}\, (d_0 - kd)^{2.5} \qquad (12)$$

This can be further verified by plotting $W^{0.4}$ vs. D_0 which gives a straight line as shown below.

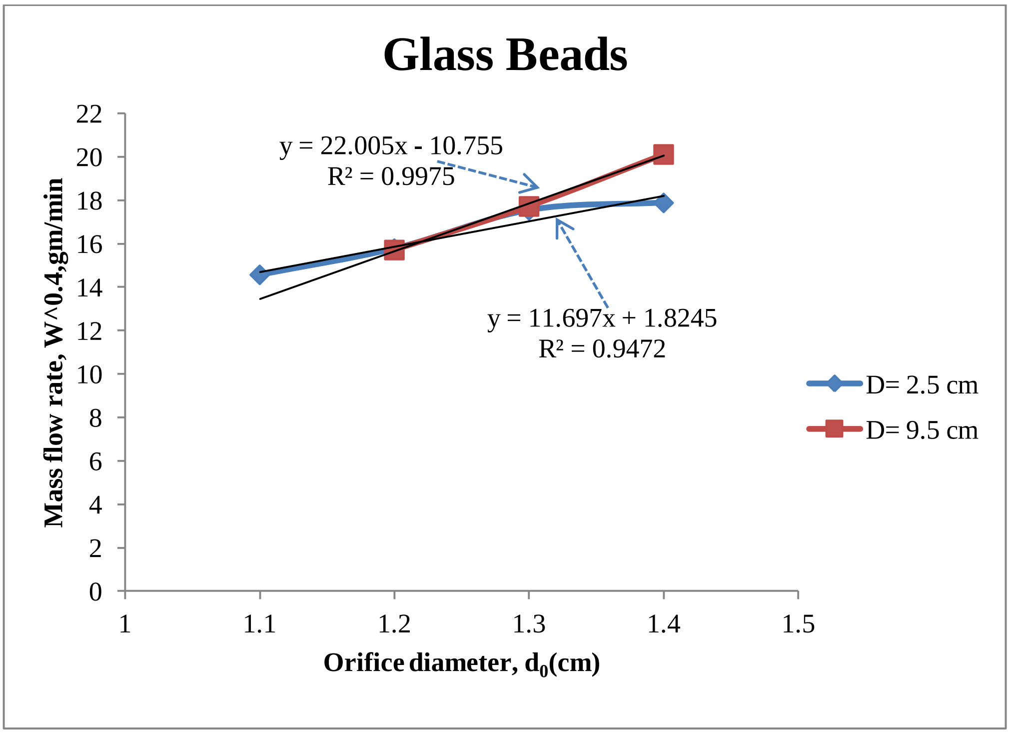

Fig 9:- Mass flow rate($W^{0.4}$)(gm/min) vs orifice diameter(cm) for glass beads.

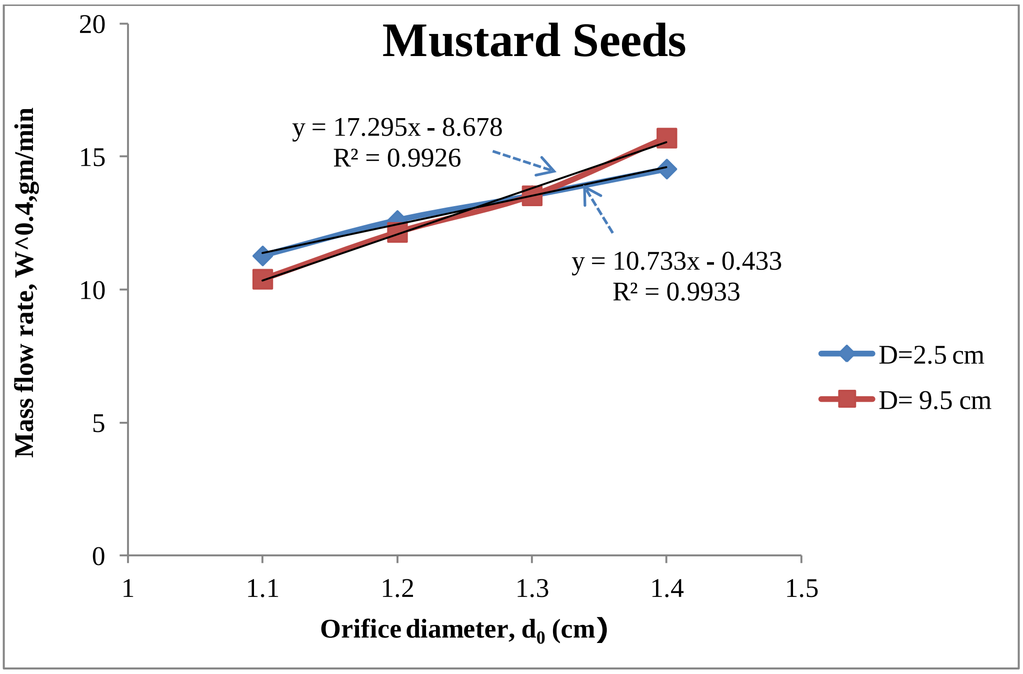

Fig 10:- Mass flow rate($W^{0.4}$)(gm/min) vs orifice diameter(cm) for mustard seeds.

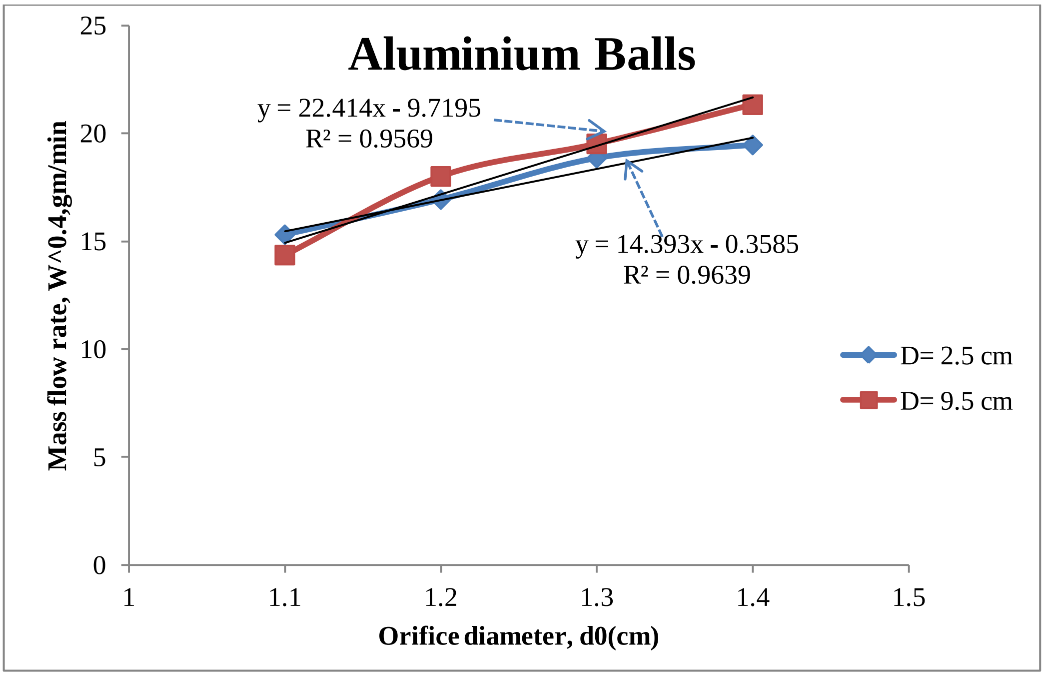

Fig 11:- Mass flow rate($W^{0.4}$)(gm/min) vs orifice diameter(cm) for aluminium balls.

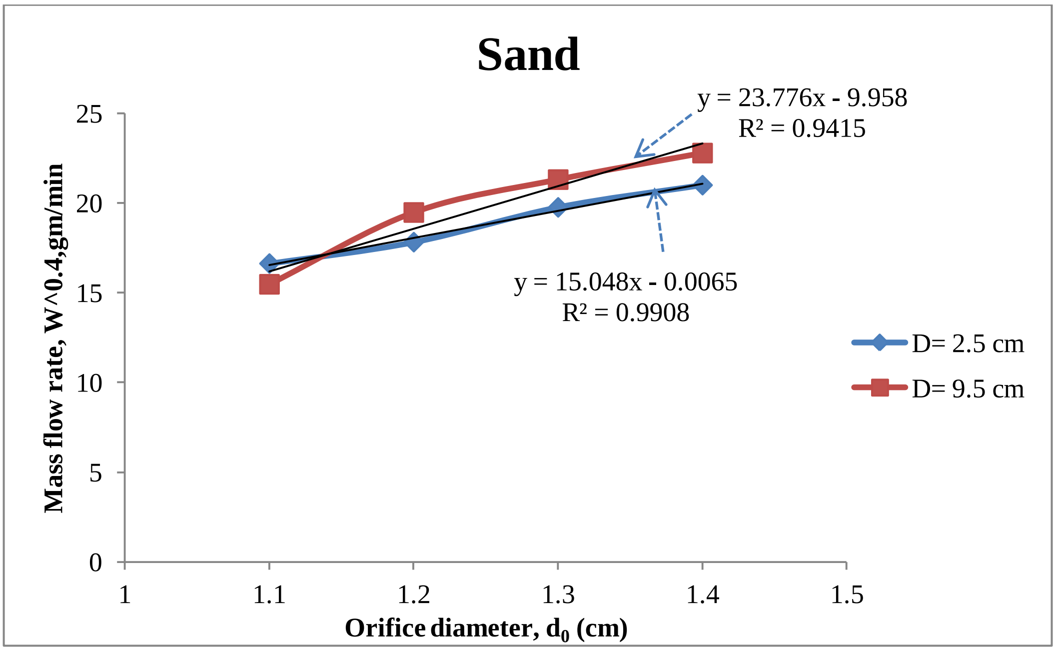

Fig 12:- Mass flow rate($W^{0.4}$)(gm/min) vs orifice diameter(cm) for sand.

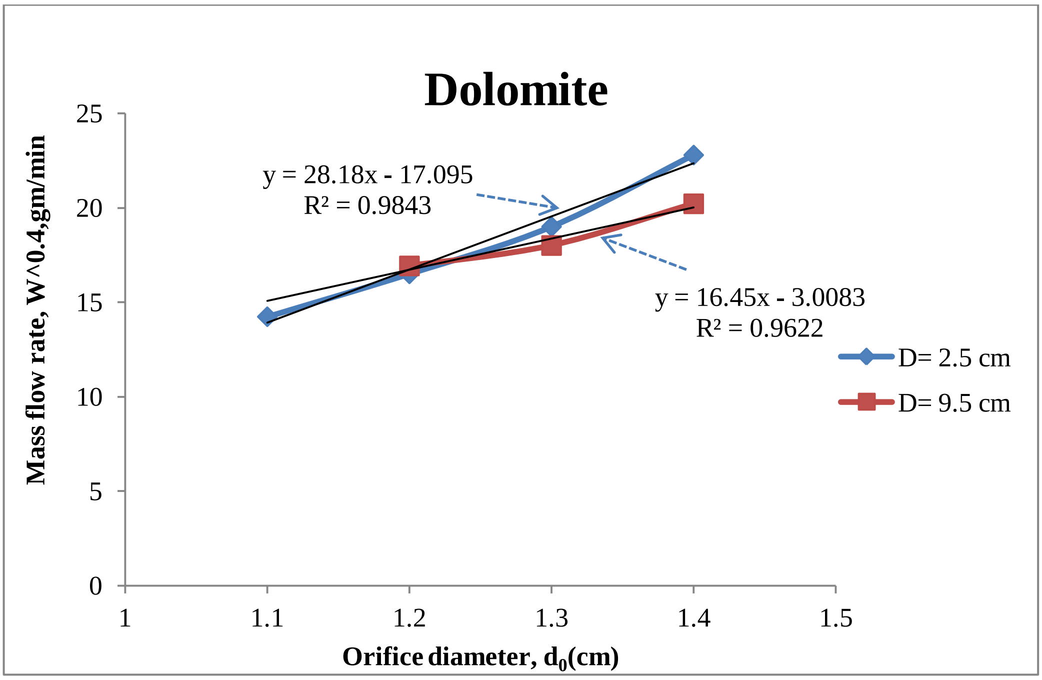

Fig 13:- Mass flow rate($W^{0.4}$)(gm/min) vs orifice diameter(cm) for dolomite.

The intercept from the graph would give us the value of k. The value of k can also be found out by substituting the values in the general equation. Thus the mass flow rates of the granular materials can be correlated with the parameters as shown below:

For Glass Beads: $W=21.72\rho_B\ g^{0.5}\ (d_0 - 1.072d)^{2.5}$

For Mustard Seeds: $W=54.25\rho_B\ g^{0.5}\ (d_0 - 3.224d)^{2.5}$

For Aluminium Balls: $W=34.45\rho_B\ g^{0.5}\ (d_0 - 2.434d)^{2.5}$

For Sand: $W=44.77\rho_B\ g^{0.5}\ (d_0 - 4.5d)^{2.5}$

For Dolomite: $W=48.54\rho_B\ g^{0.5}\ (d_0 - 4d)^{2.5}$

4.4 COMPARISON OF THEORETICAL MODEL WITH EXPERIMENTAL DATA

After deriving the general empirical formula for the granular materials as shown above, it was validated by comparing with experimental flow rates observed and error percent was calculated for all the granular materials.

Tab 9:- Calculation of error percent for glass beads.

Orifice dia (cm)	Theoretical mass flow rate(g/min)	Observed mass flow rate of Glass Beads(g/min)		Error%	
		D=2.5 cm	D=9.5 cm	D=2.5 cm	D=9.5 cm
1.1	772.66	811	----	4.96	----
1.2	1009.59	989	979	2.04	3.03
1.3	1285.49	1289	1249	0.27	2.84
1.4	1602.28	1353	1815	15.56	13.28

Tab 10:- Calculation of error percent for mustard seeds.

Orifice dia (cm)	Theoretical mass flow rate(g/min)	Observed mass flow rate of Mustard seeds(g/min)		Error%	
		D=2.5 cm	D=9.5 cm	D=2.5 cm	D=9.5 cm
1.1	374.05	426	348	13.89	6.96
1.2	535.31	586	619	9.47	15.63
1.3	732.38	674	673	7.97	8.11
1.4	967.56	805	976	16.80	0.87

Tab 11:- Calculation of error percent for aluminium balls.

Orifice dia (cm)	Theoretical mass flow rate(g/min)	Observed mass flow rate of Aluminium balls(g/min)		Error%	
		D=2.5 cm	D=9.5 cm	D=2.5 cm	D=9.5 cm
1.1	861.29	914	781	6.12	9.32
1.2	1173.51	1179	1375	0.47	17.17
1.3	1545.32	1542	1474	0.21	4.62
1.4	1980.09	1670	2100	15.67	6.06

Tab 12:- Calculation of error percent for sand.

Orifice dia (cm)	Theoretical mass flow rate(g/min)	Observed mass flow rate of Sand(g/min)		Error%	
		D=2.5 cm	D=9.5 cm	D=2.5 cm	D=9.5 cm
1.1	1064.34	1128	942	5.98	11.50
1.2	1414.47	1341	1674	5.19	18.35
1.3	1825.91	1736	1858	4.92	1.76
1.4	2301.87	2022	2479	12.16	7.70

Tab 13:- Calculation of error percent for dolomite.

Orifice dia (cm)	Theoretical mass flow rate(g/min)	Observed mass flow rate of Dolomite(g/min)		Error%	
		D=2.5 cm	D=9.5 cm	D=2.5 cm	D=9.5 cm
1.1	697.71	764	---	9.50	---
1.2	974.22	885	1177	9.16	20.80
1.3	1307.79	1245	1292	4.80	1.21
1.4	1838.65	1424	1837	22.60	0.09

4.5 CALCULATION OF VELOCITY PROFILE IN THE COLUMNS

The velocity field in the column has very interesting and complex properties. Here the velocity fluctuations have been observed at selected heights from bottom of the flat bottom column. The upper surface of the granular materials made flat after filing, altered its profile while the material flowed. It almost becomes conical in the final stages of the flow. In the stagnant zones at the sides of the funnel flow, the measured velocities were zero. The high velocity flow region was located in the vicinity of the orifice. The flow observed was almost symmetrical.

An empirical description of velocities in the column was carried out. A Gaussian solution for velocity distribution in a silo was presented by Choi et al[11] as:-

$$v(x,z) = \frac{Q}{\sqrt{4\pi bz}} e^{-x^2/4bz} \quad (13)$$

where v(x,z) denotes velocity at a point, Q is the flow rate and z is the selected height. The constant of proportionality *b* is commonly called kinematic parameter. The above equation was developed for semi infinite quasi two dimensional system ($-\infty < x < +\infty$) with orifice at z= 0 which acts like a source of velocity. The value of *z* can be varied from 5 cm to 60 cm. In this empirical model the real position of orifice makes no significant difference in the analyzed measurements.

The kinematic parameter has been investigated and suggested by various researchers. For example b = 2.24d for various particle sizes (by Tuzun and Nedderman)[12], b = 2d for iron ore particles (by Mullins)[13], b = 3.5d for glass beads (by Samadani)[14].

A sample calculation has been done for glass beads (d = 0.2cm) using the equation suggested by Choi.

Tab 14:- Velocity of glass beads at height 5cm and 10cm for column of 2.5cm.

x(cm)	Velocity of Glass Beads(cm/s) for D = 2.5cm							
	z = 5cm				z = 10cm			
	d_0=1.1 cm	d_0=1.2 cm	d_0=1.3 cm	d_0=1.4 cm	d_0=1.1 cm	d_0=1.2 cm	d_0=1.3 cm	d_0=1.4 cm
0	122	149.13	194.36	204.01	86.47	105.45	137.44	144.26
0.5	120.12	146.49	190.92	200.4	85.7	104.51	136.21	142.98
1	113.85	18.85	180.96	189.95	83.4	101.75	132.61	139.19
1.5	104.13	126.9	165.51	173.72	79.79	97.31	126.82	133.12
2	91.89	112.07	146.06	153.31	74.96	91.41	119.64	125.06
2.5	78.25	95.42	124.37	130.55	69.17	84.35	109.94	115.4

Tab 15:- Velocity of glass beads at height 20cm and 30cm for column of 2.5cm.

x(cm)	Velocity of Glass Beads (cm/s) for D = 2.5cm							
	z = 20cm				z = 30cm			
	d_0=1.1 cm	d_0=1.2 cm	d_0=1.3 cm	d_0=1.4 cm	d_0=1.1 cm	d_0=1.2 cm	d_0=1.3 cm	d_0=1.4 cm
0	61.14	74.56	97.18	102.01	49.93	60.88	79.35	83.29
0.5	60.87	74.23	96.75	101.56	49.78	60.7	79.12	83.05
1	60.06	73.24	95.46	100.20	49.33	60.16	78.41	82.3
1.5	58.74	71.63	93.35	97.98	48.6	59.27	77.25	81.09
2	56.93	69.42	90.48	94.97	47.6	58.04	75.65	79.41
2.5	54.69	66.69	86.42	91.23	46.34	56.51	73.65	77.31

Tab 16:- Velocity of glass beads at height 5cm and 10cm for column of 9.5cm.

x(cm)	Velocity of Glass Beads (cm/s) for D = 9.5cm							
	z = 5cm				z = 10cm			
	d_0=1.1 cm	d_0=1.2 cm	d_0=1.3 cm	d_0=1.4 cm	d_0=1.1 cm	d_0=1.2 cm	d_0=1.3 cm	d_0=1.4 cm
0	---	147.62	188.33	273.68	---	104.38	133.17	193.52
2	---	110.93	141.53	205.66	---	90.49	115.44	167.76
4	---	47.08	60.06	87.28	---	58.95	75.20	109.82
6	---	11.28	14.34	20.91	---	28.86	36.82	53.51
8	---	1.53	1.95	2.83	---	10.61	13.54	19.67
9	---	0.45	0.58	0.84	---	5.78	7.38	10.73

Tab 17:- Velocity of glass beads at height 20cm and 30cm for column of 9.5cm.

x(cm)	Velocity of Glass Beads (cm/s) for D = 9.5 cm							
	z = 20cm				z = 30cm			
	d_0=1.1 cm	d_0=1.2 cm	d_0=1.3 cm	d_0=1.4 cm	d_0=1.1 cm	d_0=1.2 cm	d_0=1.3 cm	d_0=1.4 cm
0	---	73.81	94.16	136.83	---	60.27	76.89	111.73
2	---	68.72	87.67	127.41	---	57.46	73.30	106.52
4	---	55.47	70.77	102.84	---	49.81	63.55	92.35
6	---	38.81	49.51	71.95	---	39.26	50.08	72.78
8	---	23.54	30.03	43.63	---	28.13	35.88	52.14
9	---	17.38	22.17	32.22	---	22.98	29.31	42.6

Velocity profile of the glass beads was calculated and plotted against x at different heights of the column.

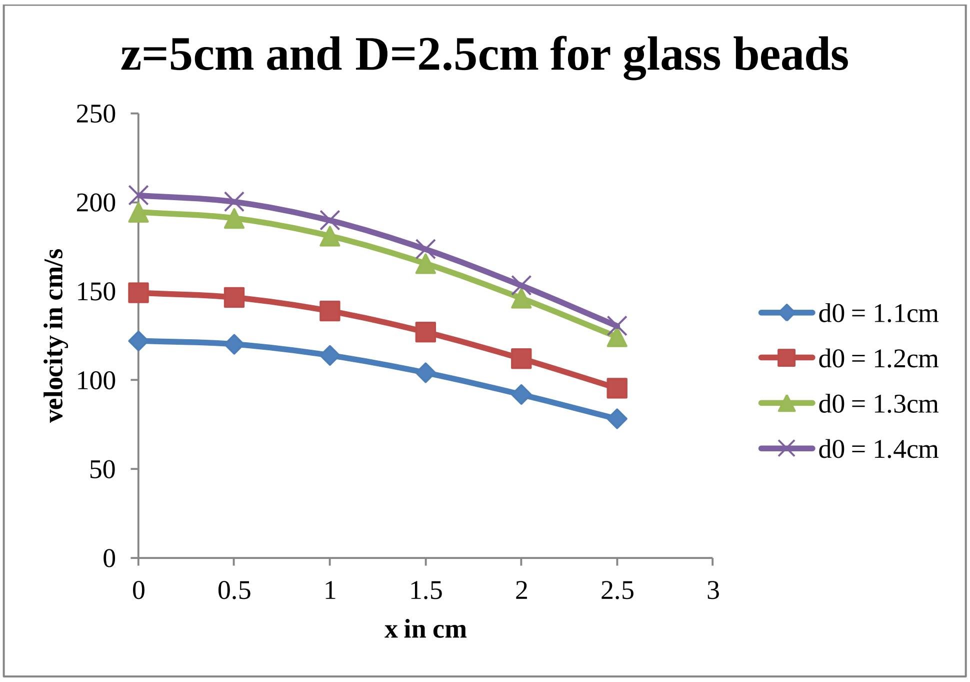

Fig 14:- Velocity (cm/s) vs. x (cm) for glass beads at z=5cm and D=2.5cm.

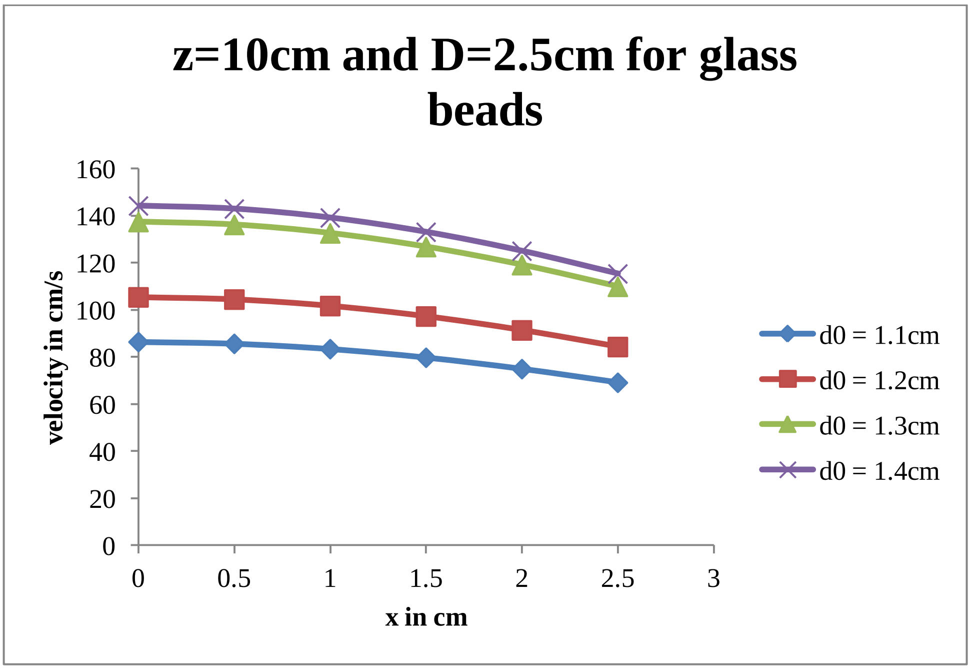

Fig 15:- Velocity (cm/s) vs. x (cm) for glass beads at z=10cm and D=2.5cm.

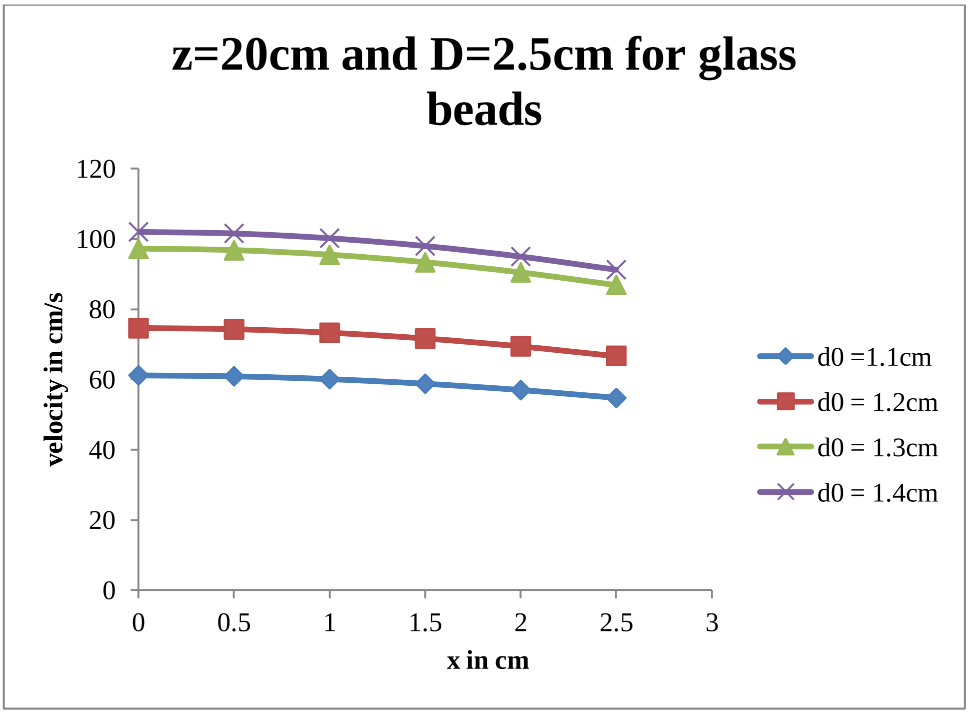

Fig 16:- Velocity (cm/s) vs. x (cm) for glass beads at z=20cm and D=2.5cm.

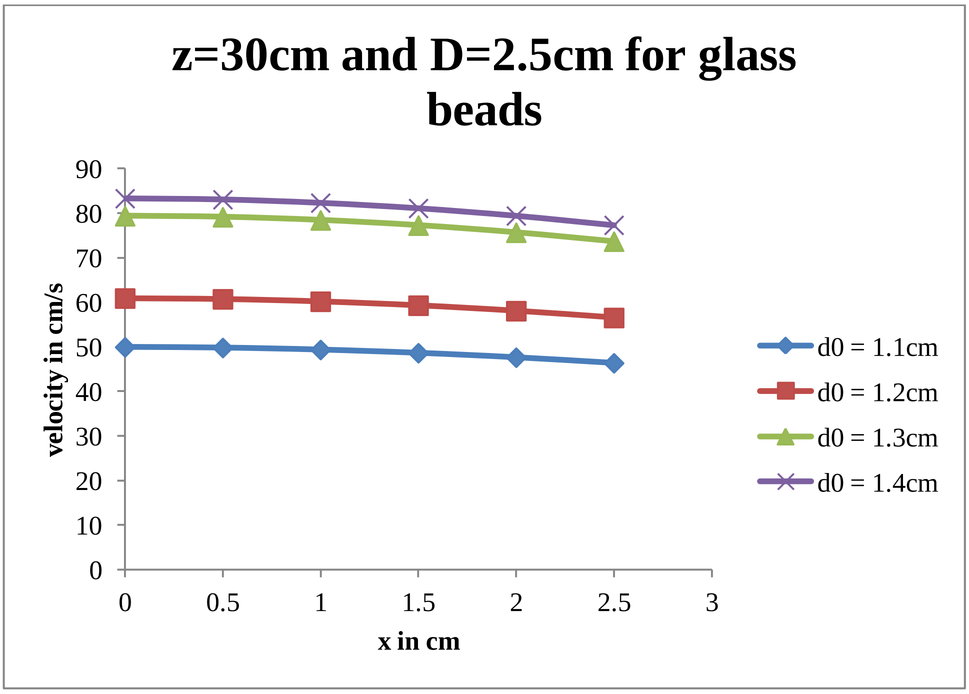

Fig 17:- Velocity (cm/s) vs. x (cm) for glass beads at z=30cm and D=2.5cm.

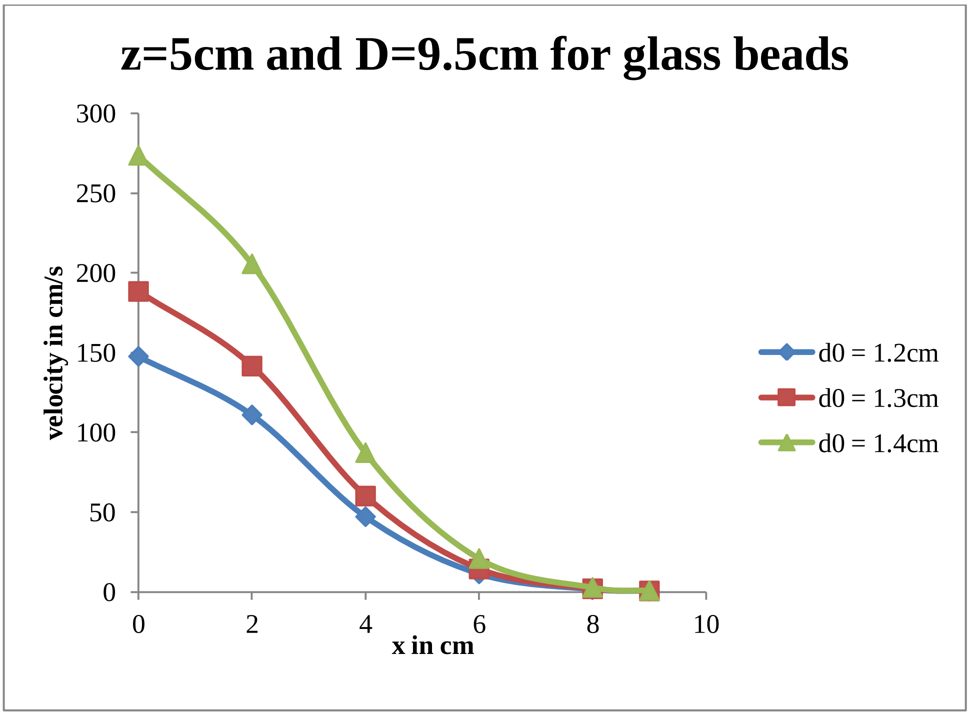

Fig 18:- Velocity (cm/s) vs. x (cm) for glass beads at z=5cm and D=9.5cm.

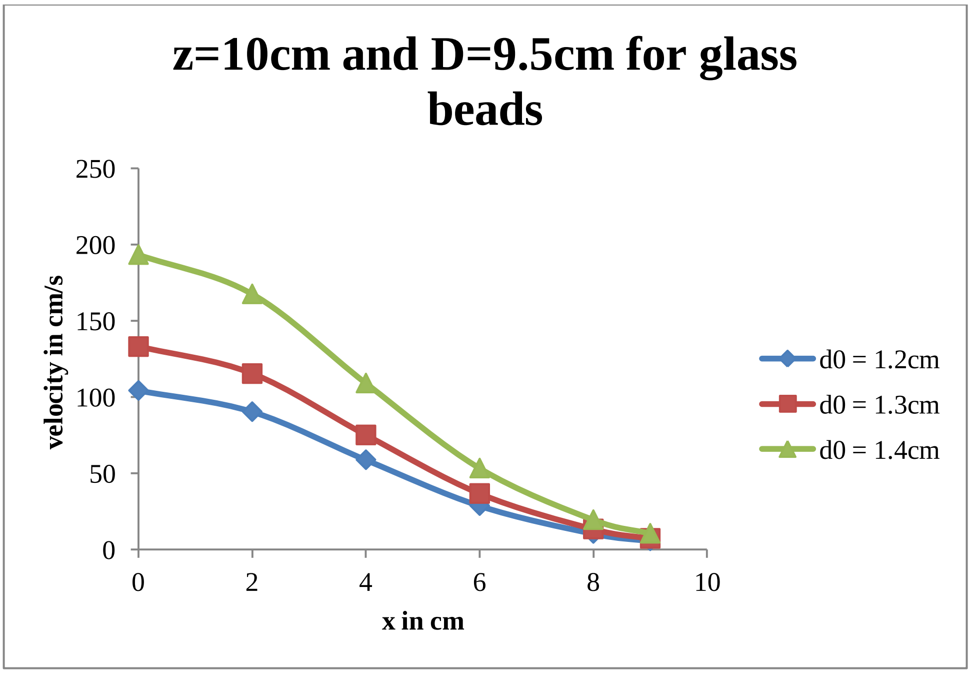

Fig 19:- Velocity (cm/s) vs. x (cm) for glass beads at z=10cm and D=9.5cm.

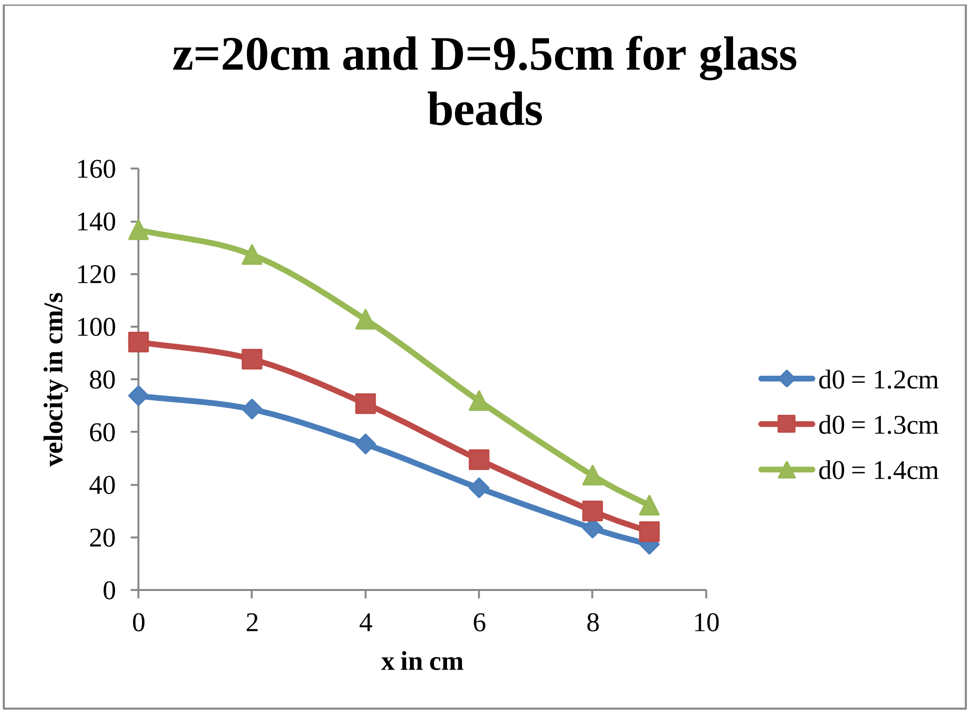

Fig 20:- Velocity (cm/s) vs. x (cm) for glass beads at z=20cm and D=9.5cm.

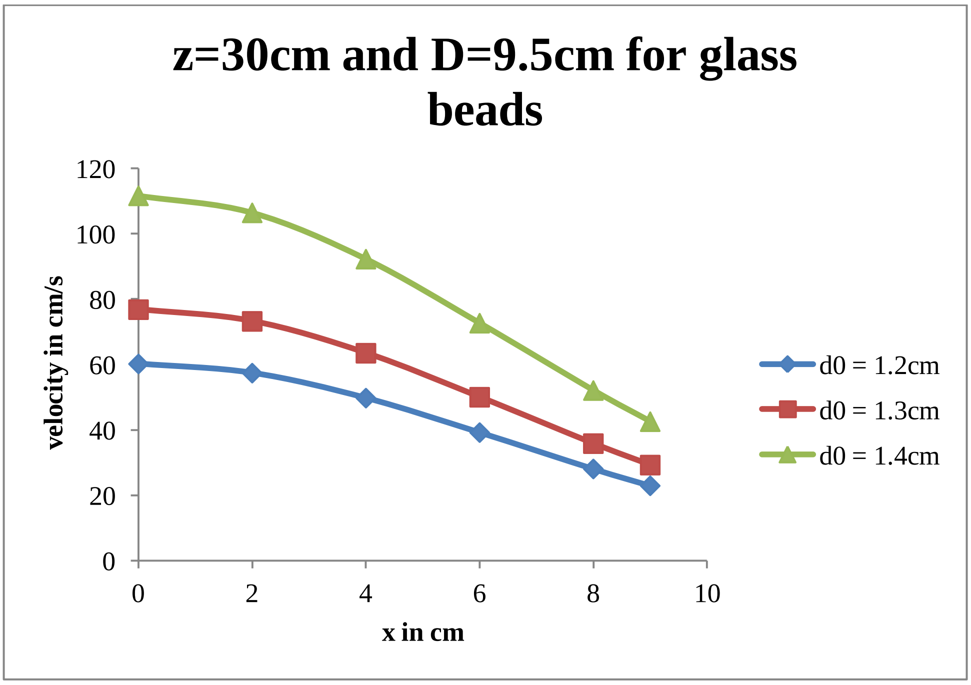

Fig 21:- Velocity (cm/s) vs. x (cm) for glass beads at z=30cm and D=9.5cm.

It can be observed from graph that with increasing orifice diameter the velocity of the glass beads increases and the velocity is maximum at lower height i.e. near the orifice of the column. Towards the wall of the column the velocity of the beads decreases and almost becomes zero.

4.6 FUTURE WORK

To confirm the veracity of the velocity obtained by theoretical model, Digital Particle Image Velocimetry(DPIV) is to be carried out. DPIV is often used to record flows in silo models or two dimensional structures. Typical DPIV apparatus consists of digital camera, a strobe/laser with optical arrangement to limit the physical region illuminated and synchronizer to act as external trigger to control camera and laser. Recorded images are to be processed and the velocities of flowing materials are obtained. DPIV is used to obtain instantaneous velocity measurements and related properties in flow.

Modeling of the granular flow in the flat bottom columns can be done by Computational Fluid Dynamics(CFD) using suitable software like Ansys.

CHAPTER 5

CONCLUSION

5. CONCLUSION

A granular material can be defined as any material composed of many individual solid particles irrespective of particle size. The term granular material embraces a wide variety of materials from the coarsest colliery rubble to the finest sugar powder. The handling of granular material is of greatest importance in the chemical industries, it being estimated on the weight basis. When one adds the vast tonnages of wheat, sugar, iron-ore, cement, sand and gravel to stored and transported the importance of granular material has become evident.

Information on the flow rate of grain through various sizes and shapes of orifices is needed to properly size the opening for flow control during transfer of grain. The need for quantitative information on the variables determining the rate of flow through a restriction has grown the advent of large scale processes employing moving bed of granular catalyst or other solids. Knowledge of fluid flow principles is of little help in such problems, since granular material system either static or moving, deviate markedly from principles due to bridging of solids.

The experiment on the free mass discharge through the circular orifices reveals few facts and notions which are summarized below:

- The rate of discharge is independent of the diameter of the vessel and of the head of material inside the vessel as long as the diameter of the vessel is greater than about 1.5 times the orifice diameter and the head is more than twice the orifice diameter.
- A so called "empty annulus", through which there can be no flow of particles exists within the edge of the aperture. It has a width which depends on the particle properties specially the particle size. The width is related to size as kd, where the value of k increases with decrease in particle size.
- Particle flow through the orifice was spasmodic over small periods of time. The granular materials sliding down the orifice form a dome over it for a few secs. This dome breaks as soon as it is formed, material falls out and new dome takes place.
- When larger sized particles was passed through orifice(Glass beads of dia 2mm passed through 1.1cm orifice dia), jamming occurs. So the ratio of orifice diameter to particle size should be greater than 6.
- The granular material is characterized by bulk density instead of actual density. This is because some amount of void are present in the bed due to loose packing of granular materials.
- By use of curve fitting and least square method a generalized empirical relation was suggested for flow rates relating to various dependable variables.

$$W=A\rho_B\ g^{0.5}\ (d_0 - kd)^{2.5}$$

- This relation is more handy and simple as it does not require measuring of various other variables through complicated procedures. Above equation does not have shape factor (λ) or friction factor (μ) as their influence is incorporated into the density (ρ_B) and particle size (d).
- The error percent between theoretical model and experimental data varied between 0.09% to 22%. Hence the given generalized equation can be used with a degree of accuracy.

From the empirical model by Choi, the velocity profile obtained showed that with increase orifice diameter the velocity of granular particles(glass beads) increases. Moreover the velocity of granular particles increases towards the orifice of the columns.

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