A THESIS SUBMITTED ON

Studies on Fluidization Behavior of Spouted Bed and Mathematical modeling

In partial fulfillment of the requirements for the degree of

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Submitted By
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The guidance of

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CERTIFICATE

This is to certify that the thesis entitled "**Studies on Fluidization Behavior of Spouted Bed and Mathematical modeling"** submitted by **Abinash Kumar** to National Institute of Technology, Rourkela is a record of bonafide project work under my supervision and is worthy for the partial fulfillment of the degree of Master of Technology (Chemical Engineering) of the Institute. The candidate has fulfilled all prescribed requirements and the thesis, which is based on candidate's own work, has not been submitted elsewhere.

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ABSTRACT

Fluidization behavior of spouted bed for a gas-solid system has been studied by carrying out a number of experiments in a cylindrical Perspex column of 5cm diameter and 100cm height. Different system parameters investigated are particle size, initial static bed height, material density, spout velocity and spout diameter. Spout velocity was calculated with the available literature. Attempt has been made to develop correlations for the bed expansion/fluctuation ratio and the fluidization index of the system on the basis of dimensionless analysis approach. The behavior of the spouted bed was also tried to be analysed by DEM –modeling in which the governing equation of force balance has been descretized by finite element central difference method. The calculated values of the fluidization index and bed expansion ratio have been compared with the experimentally observed values. It was observed that the calculated values of the fluidization index and bed expansion ratio by both the methods (i.e. DEM and Dimensionless analysis) agree with the experimental values in most of the cases with little or negligible deviation implying the developed models to be of great importance in reality.

Chapter 1

Introduction

The spouted bed technique is a variant of fluidization. Solid materials that are too coarse and uniform in size to fluidize well may be agitated in a spouted bed. The gas enters the bed through a small opening at the central orifice of the distributer plate or to the apex of a conical base, causing the formation of a central spout in which the particles move upwards in a dilute phase. The annular space between the spout and the vessel wall contains a packed bed of particles, moving slowly downwards and radially inwards. The gas flares out into the annulus as it travels upwards, rapidly at first and then more gradually, but the gas velocity in the annulus remains below the velocity necessary to fluidize the annular solids. The technique has proved to be of interest for a variety of processes involving coarse solids, such as drying, cooling, coating and blending of granular materials, granulation of fertilizer, carbonization of coal and pyrolysis of shale'. The spouted bed has been used successfully in the polymerization of benzyl alcohol on acidic catalysts and in coal gasification.

The advantages of the spouted beds over the conventional bubbling gas fluidized beds lie in its ability to process coarse, sticky and heat-sensitive materials. Spouted beds are widely used in industry for handling and processing of particulate solids.

Its application in operations or processes requires the determination of the design conditions. The definition of the hydrodynamics of the spouted bed is very limited and the only correlations for its design can be established from many experimental results and analysis.

Spouting which is a visually observable phenomenon, occurs over a defined range of gas velocity for a given combination of gas solid and vessel configuration. The transition from a quiescent to a spouting to a bubbling (poor quality aggregative fluidization) to a slugging bed often occurs as gas velocity is increased. Fluid is injected through a small opening located at the base of an open vessel filled with relatively coarse particulate solids. If the fluid injection rate is high enough, the resulting high velocity jet causes a stream of particles to rise rapidly in to a hollowed central core within the bed of solids which is termed as spouted bed. The central core is called the spout and the principal annular reason is called annulus. The term fountain is used to denote the mushroom-shape zone above the level of annulus [(1).]

The present work is based on the study of fluidization behavior of spouted bed using different system parameters like spout diameter, particle size, static bed height, spouting velocity and density of bed materials and thereby to develop correlations for bed expansion/fluctuation ratio and fluidization index. Although some basic formulas for spouted beds are already developed by some researchers but the detail analysis with varying system parameters are required to be investigated. As it is difficult to determine the axial velocity profile of particle, fluid and void volume fraction experimentally, attempt has been made for mathematical modeling of the spouted bed system for determination of void volume fraction, particle’s velocity profile and other dynamics. In the present work attempt has also been made to use DEM for analysis of the spouted bed system.

Chapter 2

Literature survey

The spouted beds, originally invented in Canada by Mathur and Gishler (1955) as an alternative to fluidized beds for handling coarse particles, are now widely applied in various physical operations such as drying, coating and granulation[2] . The distinctive advantages of spouted beds as reactors for various chemical processes are also well recognized in recent years.

In addition to their ability to handle coarse particles, spouted beds also possess certain structural and flow characteristics that are very desirable in some chemical reaction systems. For example, the toroidal nature of particle motion in spouted beds makes it possible to recirculate heat in an organized manner, thus leading to extended ranges of flammability, enhanced reaction rates, and super-adiabatic temperatures, considerably higher than the adiabatic flame limit of premixed reactants for a given preheat temperature [3] Consequently, increasing attention has been paid to the application of spouted beds as chemical reactors, including as combustion reactors.

Attempt has been made to develop theoretical model for the prediction of spout diameter in a spouted bed [4]. An equation has been derived from a force balance analysis, in addition to the hydrodynamic forces for spout diameter which also takes into account the solid stresses based on hopper flow of solids. The functional form of the equation is supported by a wide range of experimental data, the value of the multiplying coefficient showing an order of magnitude agreement with the empirical value. The theoretical analysis, though less comprehensive than a previous one [5] leads to a spout diameter equation which shows a greater measure of agreement with experimental results than the earlier equation.

In the computational fluid dynamics (CFD) modeling of gas–solids two-phase flows, drag force is the only accelerating force acting on particles and thus plays an important role in coupling two phases. To understand the influence of drag models on the CFD modeling of spouted beds, several widely used drag models available in literature. Among the different drag models discussed, the Gidaspow model [6,7] gave the best agreement with experimental observation both qualitatively and quantitatively. Their investigation showed that drag models had critical and subtle impacts on the CFD predictions of dense gas–solids two-phase systems such as encountered in spouted beds[8].

Spouted beds are a variant of fluidization which permit good gas-solids contact with solid materials commonly too coarse or dense for stable fluidization. These particles have been categorized by Geldart as Group D. The spouted state is formed by forcing gas upwards through a small orifice at the base of a bed of particles rather than by distributing the gas evenly as at the base of an ordinary fluidized bed. At a large enough flow-rate, gas penetrates right through the bed as a high velocity jet or spout. The spout accelerates particles from its interface with the surrounding annulus and carries them up to form a fountain at the top of the bed. This causes a general downwards solids flow in the annulus with individual particles being picked up and accelerated upwards once again at the spout/annulus interface. The minimum superficial velocity at which the general circulation is just maintained is known as the minimum spouting velocity.

The spouted bed gasification of coal is attracting interest at the present time, because the technique allows oxygen to reach a higher proportion of the bed particles than in a normal fluidized bed in which much of the oxygen is consumed just above the gas distributor The need to supply plenty of oxygen to the bed also means that spouted bed gasifiers working at pressure have been suggested.

In addition to the experimental works as summarized [9], there is a growing interest to use computational fluid dynamics (CFD) methods to explore the possibility of spouted beds as chemical reactors[10] . The two most commonly used methods for modeling gas–solids two-phase systems are the discrete element method (DEM) and the two fluid models (TFM). In the DEM approach, the gas phase is described by a locally averaged Navier–Stokes equation, the motion of individual particles is traced, and the two phases are coupled by interphase forces. For the TFM approach, the different phases are mathematically treated as interpenetrating continua, and the conservation equation for each of the two phases is derived to obtain a set of equations that have similar structure for each phase. Both of the two approaches are adopted in spouted bed modeling.

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2.1 Spouted Bed

A vessel is open at top and filled with relatively coarse particulates of solids. Suppose fluid is injected through a certainly located small opening at the base of the vessel. If the fluid injection rate is high enough, the resulting high velocity jet causes a stream of particles to rise rapidly in to a hollowed central core within the bed of solids. This system is termed as spouted bed, the central core is called the spout and the principle annular reason is called annulus. The spouting and its stability, operating condition, spouting bed height along with the changing phenomenon from spouting to bubbling, slugging etc. depends on many factors like effect of particle size, orifice size of spouting fluid, flow rate of fluidizing fluid, bed height and the density of particle used. For a given solid material contacted by a specific fluid in a vessel of fixed geometry, there exists a maximum spoutable bed depth Hm, beyond which the spouting action does not exists but it replaced by a poor quality fluidization . The minimum spouting velocity at this bed depth can be 1.25 to 1.5 times greater than the corresponding minimum fluidization velocity, U_{mf}.

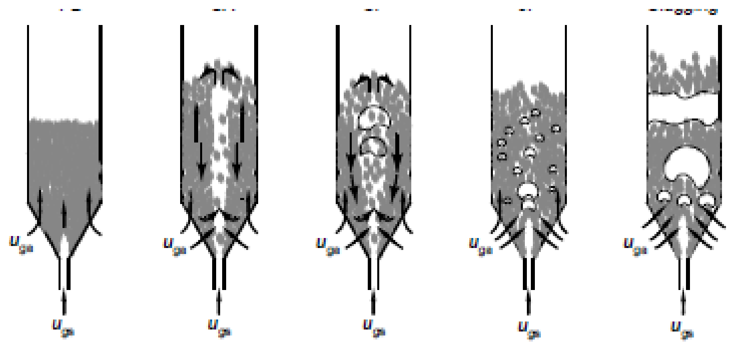


Fig. 2.1: The states of spouting to fluidization and slugging (11).

2.2 The Effect of particle size

The maximum spoutable bed height H_m with respect to particle size has been reported by several investigations (12) indicated that Hm increases with particle size d_p up to a limit and then decreases, the critical particle size commonly ranges from 1.0 to 1.5mm for the columns in different diameters. This tendency was demonstrated by later studies (13-15). In another study,[16] indicated that H_m increased when the particle diameter was increased from 0.3 to 0.45mm in an 80mm diameter flat-based column, and then H_m decreased when the particle diameter was increased from 0.65 to 1.24 mm. The results of research (17) showed that H_m increased as the particles size was increased from 0.40 to 0.71 mm, and then decreased. These studies on spouted beds showed that H_m of spouted beds decreases with increasing particle size for coarse particles. This trend of the maximum spoutable bed height respect to particle size can also be seen in the previous reports [18-19].

2.3 The Effect of spout orifice size

It can be seen that H_m of spout bed deceases with increasing spout orifice (nozzle) diameter without reference to the introduction of fluidizing gas. In the literature (20) specially studied the effect of spout nozzle diameter on H_m and demonstrated that H_m deceased with increasing spout nozzle diameter. Same tendency has been observed by later investigations indicated that H_m increased from the 2mm spout nozzle width (Di/Dt = 0.013) to the 6mm spout nozzle width (Di/Dt = 0.04) and then decreases with spout nozzle width,(21) in their later publication showed that H_m increased slightly with increasing spout nozzle size. Accor-ding to the above review, we can draw a generally conclusion that *H*m of spouted beds might decease with increa-sing spout nozzle size. In this sense, it is found that the effect of spout nozzle size on *Hm* of spoutfluid bed shares the same tendency to those of spouted beds.

2.4 The Effect of fluidizing gas flow rate

There has been little investigation [(22)] on the maximum spoutable height *H*m of a spout-fluid bed, especially the discussion on the effect of fluidizing gas flow rate on *H*m so far [(23)] theoretically studied *H*m of a spout-fluid bed under the condition that normal spouting was accompanied by additional aeration but no fluidization of the annulus. Their experiments showed that *H*m decreases with increasing fluidizing gas flow rate [(24)] studied *H*m of a flat base spout-fluid bed at minimum spout-fluidizing flow rate and obtained the same results. These studies were carried out at a narrow range of fluidizing gas flow rate (less than minimum fluidizing gas flow rate). However, previous work [(25)] illustrated that spouting and spout-fluidizing could also be observed when the fluidizing gas flow rate is larger than the minimum fluidization condition.

2.5 Mechanism behind spout termination

The mechanisms of spout termination in spouted beds have been reviewed and grouped into the following three different types when bed heights are larger than Hm [(26)].

(a) Fluidization of the annular particles

(b) Choking of the spout and

(c) Growth of instabilities at spout–annulus interface.

The mechanism of spout termination in the spout-fluid bed has not been clarified so far. However, the following discussion might be helpful. By analyzing of the flow pattern images recorded by digital CCD camera frame by frame, the mechanisms of spout termination in the spout-fluid bed is found to be slugging in the spout and growth of instabilities at the spout–annulus interface. Chocking of the spout is not the mechanism of spout termination due to the introduction of fluidizing gas into the bed, since the fluidizing gas would loosen the bed materials and benefit the spout jet to penetrate the bed [(27-29)].

However, on the other hand, the fluidizing gas easily dissipates the spouting gas momentum as the spout jet ascends in the bed, and large bubbles easily form in the upper region of the bed [(29-31)]. In this case, stable spouting is difficult to obtain even at large spouting gas flow rate. Instead, slugging caused by larger bubbles accompanied with growth of instabilities at spout–annulus interface caused by stochastic visible large bubbles in the boundary of spout jet and near the fluidizing gas distributor.

Fluidization of the annular particles is also not the mechanism of spout termination in the spout-fluid bed. The particles in the annulus can be fluidized with introduction of fluidizing gas with-out reference to bed height. When the bed material is within the maximum spoutable bed height, relatively stable flow patterns of spouting and spout-fluidizing can be achieved. At the same time, the differential pressure signals show that particles in the annular region are fluidized. Though spout termination is found when the bed material is larger than the maximum spoutable bed height, it should not consider fluidization of the annular particles to be the mechanism of spout termination in the spout-fluid bed as it should be slugging in the spout and growth of instabilities at the spout–annulus interface.

2.6. Expansion Ratio

This term is used to describe the characteristics of bed height during fluidization. This is quantitatively defined as the ratio of average bed height to the static bed height. Average bed height is the arithmetic mean of highest and lowest level occupied by top of the bed. It is denoted by ‘R’. The term used in the spouted bed having the same meaning at fluidization condition.

$$R = (H_{avg} / H_{static}) = ((H_{max} + H_{min})/2)/ H_{static}) \qquad (2.1)$$

2.7 Fluctuation Ratio

The term fluctuation ratio used to describe the characteristics of the bed height during fluidization. This is quantitatively defined as the ratio of the highest and lowest levels which the top of the bed occupies for any particular gas flow rate. It is denoted by ‘r’.

$$r = (H_{max} / H_{min}) \qquad (2.2)$$

2.8 Fluidization Index

Fluidization index is the ratio of pressure drop across the bed to the weight force exerted by the bed material per unit area of cross-section of the column. For ideal fluidization, fluidization index is 1.But it should high for the spouting bed.

$$F.I. = (\Delta P / (W_f / A)) \qquad (2.3)$$

Chapter 3

Mathematical modeling

The basic equation of motion for single phase flows was initially developed by Navier in 1822 in the form of well known Navier – Stokes equation. The Navier-Stokes equations were extended to multiphase flow by using volume averaging of the single phase equation and adding appropriate terms. Soo in 1967 suggested that particles of identical diameter and density should form a continuum or a particulate phase. It follows that if two different particle sizes are required in the fluidized bed then there should be two particulate phases. These phases can be treated like a pseudo fluids where they are considered to form the interpenetrating continua. This technique is known as Eulerian – Eulerian method. Witt (1997) showed that the Eulerian – Eulerian method is the most promising method for simulating spouted bed and fluidized bed system. The following two approaches for the numerical calculations of multiphase flows are currently used.

3.1 EULER – LANGRANGE APPROACH

The fluid phase is treated as a continuum by solving the time-averaged Navier- Stokes equations, while the dispersed phase is solved by tracking a large number of particles, bubbles, or droplets through the calculated flow field. The dispersed phase can exchange momentum, mass and energy with the fluid phase. A fundamental assumption made in this model is that the dispersed second phase occupies a low volume fraction, even though high mass loading; mass of particle is higher than fluid is acceptable. The particle or droplet trajectories are computed individually at specified intervals during the fluid phase calculation. This makes the model appropriate for the modeling of spray dryers, coal and liquid fuel combustion, and some particle laden flows, but inappropriate for the modeling of liquid-liquid mixtures, fluidized beds or any application where the volume fraction of the second phase is not negligible

3.2 EULER – EULER APPROACH

In the Euler-Euler approach the different phases are treated mathematically as interpenetrating continua. Since the volume of a phase cannot be carried occupied by the other phases, the concept of the volume fraction is introduced. These volume fractions are assumed to be continuous functions of space and time and their sum is equal to one. Conservation equations for each phase are derived to obtain a set of equations, which have similar structure for all phases. These equations are closed by providing constitutive relations that are obtained from empirical information or in the case of granular flows by application of kinetic theory so we can apply this to many fluidization and spouting problems.

3.3 Basic equations for the spouted bed

The Ums and other formulas used in the dealings of spouted bed was as given below.

$$U_{ms} = (d_p / D_c)(d_i / D_c)^{1/3}((2 * g * H_s * (\rho_s - \rho_f)) / \rho_f)^{1/2} \quad (3.1)$$

(a) Particle's mean velocity

$$\frac{dV_s}{dt} = \frac{3}{4} * \frac{C_d}{d} * \frac{\rho_f}{\rho_s} * (u_s - u_f)^2 - (\frac{\rho_s - \rho_f}{\rho_s}) * g \quad (3.2)$$

(b) Spout Diameter

$$d_s = (.115 \log_{10} D_c - .31)\sqrt{G} \quad (3.3)$$

(c) Maximum Spoutable Bed Depth

$$\frac{dV_s}{dt} = \frac{3}{4} * \frac{C_d}{d} * \frac{\rho_f}{\rho_s} * (u_s - u_f)^2 - (\frac{\rho_s - \rho_f}{\rho_s}) * g \quad (3.4)$$

(d) Spouting Pressure Drop

$$\Delta P = 2Hms * \rho_s * (g / g_c) * ((1 - \varepsilon_o) / \Pi) \quad (3.5)$$

(e) Spout Voidage value

$$\varepsilon_s = 2.17(\mathrm{Re}/Ar)^{0.33}(H/d_i)^{-0.5}(\tan\theta/2)^{-0.6} \qquad (3.5.a)$$

The mathematical models consist of equations of particle motion and equation of fluid.

(f)The mass conservative equation for phase m (m= gas, solid) is

$$\frac{\partial(\varepsilon_i\rho_i)}{\partial t} = -\nabla.(\varepsilon_i\rho_i v_i) \qquad (3.6)$$

(g) Momentum conservation equation

For gas phase [32]

$$\frac{\partial(\varepsilon_g\rho_g v_g)}{\partial t} + \nabla.(\varepsilon_g\rho_g v_g v_g) = -\varepsilon_g\nabla P + \nabla.\tau_g + \varepsilon_g\rho_g g - \beta(v_g - v_s) \qquad (3.7)$$

For the solid phase

$$\frac{\partial(\varepsilon_s\rho_s v_s)}{\partial t} + \nabla.(\varepsilon_s\rho_s v_s v_s) = -\varepsilon_s\nabla P + \nabla.\tau_s + \varepsilon_s\rho_s g + \beta(v_g - v_s) - \nabla P_s \qquad (3.8)$$

Where u_p is the particle velocity vector averaged in a cell. The coefficient β depends on the void fraction given by [33] .

$$\beta = \frac{\mu(1-\varepsilon)}{d_p^2\varepsilon}[150(1-\varepsilon) + 1.75R_e] \quad (\varepsilon \leqslant 0.8), \qquad (3.9)$$

$$\beta = \frac{3}{4}C_D\frac{\mu(1-\varepsilon)}{d_d^2}\varepsilon^{-2.7}R_e \quad (\varepsilon > 0.8), \qquad (3.10)$$

Where d_p is the particle diameter and μ is the fluid viscosity. C_D is the drag force on each single particle given by

$$C_D = 24(1 + 0.15\mathrm{Re}^{0.687})/\mathrm{Re} \quad (R_e \leqslant 1000), \qquad (3.11)$$

$$C_D = 0.43 \quad (R_e > 1000), \qquad (1.12)$$

Where

$$R_e = \frac{|\vec{u}_p - \vec{v}|\rho\varepsilon d_p}{\mu}. \qquad (3.13)$$

The equation of fluid motion was solved simultaneously with the equation of particle motion using Discrete Element Method.

3.4 **Discrete element method**

In mathematics, discretization concerns the process of transferring continuous models and equations into discrete counterparts. This process is usually carried out as a first step toward making them suitable for numerical evaluation and implementation on digital computers. In order to be processed on a digital computer another process named quantization is essential. The stability of the chosen discretization is generally established numerically rather than analytically as with simple linear problems. Special care must also be taken to ensure that the discretization handles discontinuous solutions gracefully. The Euler equations and Navier-Stokes equations both admit shocks, and contact surfaces. Some of the discretization methods being used are:

3.5 Finite Volume Method (FVM)

This is the "classical" or standard approach used most often in commercial software and research codes. The governing equations are solved on discrete control volumes. FVM recasts the PDE's (Partial Differential Equations) of the N-S equation in the conservative form and then discretize this equation. "Finite volume" refers to the small volume surrounding each node point on a mesh.

3.6 Finite Difference Method

Finite-difference methods approximate the solutions to differential equations by replacing derivative expressions with approximately equivalent difference quotients. then a reasonable approximation for that derivative would be to take Modern finite difference codes make use of an embedded boundary for handling complex geometries making these codes highly efficient and accurate so it is simple to program.

$$f'(a) = \lim_{h \to 0} \frac{f(a+h) - f(a)}{h} \tag{3.14}$$

Then the reasonable approximation can be

$$f'(a) \approx \frac{f(a+h) - f(a)}{h} \tag{3.15}$$

3.6 Explicit Method

Using a forward difference at time *tn* and a second-order central difference for the space derivative at position *xj* ("FTCS") we get the recurrence equation as follows.

$$\frac{u_j^{n+1} - u_j^n}{k} = \frac{u_{j+1}^n - 2u_j^n + u_{j-1}^n}{h^2} \tag{3.16}$$

This can also be written in the following form.

$$u_j^{n+1} = ru_{j+1}^n + (1-2r)u_j^n + ru_{j-1}^n \quad . \tag{3.17}$$

We can obtain from the other values this way:

Where, $r = k / h^2$. So, knowing the values at time *n* you can obtain the corresponding ones at time *n*+1 using this.

3.7 Implicit Method

If we use the backward difference at time *tn* + 1 and a second-order central difference for the space derivative at position *xj* ("BTCS") we get the recurrence equation:

$$\frac{u_j^{n+1} - u_j^n}{k} = \frac{u_{j+1}^{n+1} - 2u_j^{n+1} + u_{j-1}^{n+1}}{h^2} \tag{3.18}$$

And **Crank Nicolson** methods were easily used to solve the spouted bed continuity and momentum conservation equation to get the velocity profile and the solid volume fraction of by fixing the proper boundary conditions.

3.8 Continuity equation for the respective phases.

$$\partial\left(\varepsilon_i \rho_i\right) / \partial t = -\nabla.(\varepsilon_i \rho_i v_i) \tag{3.19}$$

We know that in the two phase modeling gaseous and solid phases are present so Here we need to discritize both phase continuity equation so that modeling of each phase should be done. Since we are dealing with the cylindrical bed so continuity equation was written in cylindrical coordinates, which is as follows.

For the gas component:

$$\partial\left(\varepsilon_g \rho_g\right) / \partial t = -\nabla.(\varepsilon_g \rho_g v_g) \tag{3.20}$$

In cylindrical coordinate

$$\partial\left(\varepsilon_g\rho_g\right)/\partial t = -\nabla.(\varepsilon_g\rho_g v_g) = -[\frac{1}{r}\frac{\partial(r\varepsilon_g\rho_g v_{rg})}{\partial r} + \frac{1}{r}\frac{\partial(\varepsilon_g\rho_g v_{\theta g})}{\partial\theta} + \frac{1}{r}\frac{\partial(r\varepsilon_g\rho_g v_{zg})}{\partial z}] \qquad (3.21)$$

Neglecting the angular part

$$= -[\frac{1}{r}\frac{\partial(r\varepsilon_g\rho_g v_{rg})}{\partial r} + \frac{1}{r}\frac{\partial(r\varepsilon_g\rho_g v_{\theta g})}{\partial z}] \qquad (3.22)$$

Now the equation is

$$\partial\left(\varepsilon_g\rho_g\right)/\partial t = -\nabla.(\varepsilon_g\rho_g v_g) = -[\frac{1}{r}(r\varepsilon_g\rho_g\frac{\partial(v_{rg})}{\partial r} + r\rho_g\frac{\partial(\varepsilon_g)}{\partial r}v_{rg} + \varepsilon_g\rho_g v_{rg}) + \varepsilon_g\rho_g\frac{\partial(v_{zg})}{\partial z} + \rho_g v_{zg}\frac{\partial(\varepsilon_g)}{\partial z}]$$

or, (3.23)

$$\partial\left(\varepsilon_g\rho_g\right)/\partial t = -\nabla.(\varepsilon_g\rho_g v_g) = -[(\varepsilon_g\rho_g\frac{\partial(v_{rg})}{\partial r} + \rho_g\frac{\partial(\varepsilon_g)}{\partial r}v_{rg} + \frac{1}{r}\varepsilon_g\rho_g v_{rg}) + \varepsilon_g\rho_g\frac{\partial(v_{zg})}{\partial z} + \rho_g v_{zg}\frac{\partial(\varepsilon_g)}{\partial z}]$$

(3.24)

This equation can be discretize by applying explicit with central difference method discretize equation can be written as

$$\frac{(\varepsilon_g\rho_g)_{i,j}^{t+\Delta t} - (\varepsilon_g\rho_g)_{i,j}^{t}}{\Delta t} = [(\varepsilon_g\rho_g)_{i,j}^{t}\frac{(\varepsilon_g\rho_g)_{i+1,j}^{t} - (\varepsilon_g\rho_g)_{i-1,j}^{t}}{2\Delta r} + (v_{rg}\rho_g)_{i,j}^{t}\frac{(\varepsilon_g)_{i+1,j}^{t} - (\varepsilon_g)_{i-1,j}^{t}}{2\Delta r}$$
$$+(\frac{1}{r}\varepsilon_g\rho_g v_{rg})_{i,j}^{t}) + (\varepsilon_g\rho_g)_{i,j}^{t}\frac{(v_{zg})_{i+1,j}^{t} - (v_{zg})_{i-1,j}^{t}}{2\Delta r} + (v_{zg}\rho_g)_{i,j}^{t}\frac{(v_{zg})_{i,j+1}^{t} - (v_{zg})_{i,j-1}^{t}}{2\Delta z}]$$

(3.25)

Since the above term contains 'r' in denominator and at r=0, it will be infinity so we apply the L.Hospitals rule the remove the 'r' term so the continuity equation becomes

$$\frac{(\varepsilon_g\rho_g)_{i,j}^{t+\Delta t} - (\varepsilon_g\rho_g)_{i,j}^{t}}{\Delta t} = [2(\varepsilon_g\rho_g)_{i,j}^{t}\frac{(\varepsilon_g\rho_g)_{i+1,j}^{t} - (\varepsilon_g\rho_g)_{i-1,j}^{t}}{2\Delta r} + (v_{rg}\rho_g)_{i,j}^{t}\frac{(\varepsilon_g)_{i+1,j}^{t} - (\varepsilon_g)_{i-1,j}^{t}}{2\Delta r}$$
$$+(\varepsilon_g\rho_g)_{i,j}^{t}\frac{(v_{zg})_{i+1,j}^{t} - (v_{zg})_{i-1,j}^{t}}{2\Delta r} + (v_{zg}\rho_g)_{i,j}^{t}\frac{(v_{zg})_{i,j+1}^{t} - (v_{zg})_{i,j-1}^{t}}{2\Delta z}] \qquad (3.26)$$

Similarly the solid phase equation can be written as

$$\frac{(\varepsilon_s\rho_s)_{i,j}^{t+\Delta t} - (\varepsilon_s\rho_s)_{i,j}^{t}}{\Delta t} = [2(\varepsilon_s\rho_s)_{i,j}^{t}\frac{(\varepsilon_s\rho_s)_{i+1,j}^{t} - (\varepsilon_s\rho_s)_{i-1,j}^{t}}{2\Delta r} + (v_{rs}\rho_s)_{i,j}^{t}\frac{(\varepsilon_s)_{i+1,j}^{t} - (\varepsilon_s)_{i-1,j}^{t}}{2\Delta r}$$
$$+(\varepsilon_s\rho_s)_{i,j}^{t}\frac{(v_{zs})_{i+1,j}^{t} - (v_{zs})_{i-1,j}^{t}}{2\Delta r} + (v_{zs}\rho_s)_{i,j}^{t}\frac{(v_{zs})_{i,j+1}^{t} - (v_{zs})_{i,j-1}^{t}}{2\Delta z}] \qquad (3.27)$$

3.9 Momentum balance equation

Momentum balance equation for the gas- solid phase can be written in the form of cylindrical coordinate. [34]

r-momentum equation

$$\varepsilon_s\rho_s\frac{\partial v_{rg}}{\partial t}+\frac{\varepsilon_s\rho_s v_{rg}}{r}\frac{\partial v_{rg}}{\partial r}+\varepsilon_s\rho_s v_{zg}\frac{\partial v_{rg}}{\partial z}=\frac{1}{r}\frac{\partial(r\varepsilon_g\tau_{rr})}{\partial r}+\frac{1}{r}\frac{\partial(\varepsilon_g\tau_{\theta r})}{\partial\theta}+$$

$$\frac{\partial(\varepsilon_g\tau_{rz})}{\partial z}-\frac{\tau_{\theta\theta}\varepsilon_g}{r}-f_{gs}+\varepsilon_g\rho_g g \qquad (3.28)$$

Where,

$$\tau_{rr}=2\mu\frac{\partial v_{rg}}{\partial r}-\frac{2}{3}\mu(\nabla.v) \qquad (3.29)$$

$$\tau_{rr}=+\mu[\frac{\partial v_{rg}}{\partial z}+\frac{\partial v_{zg}}{\partial r}] \qquad (3.30)$$

$$\tau_{\theta\theta}=2\mu[\frac{1}{r}\frac{\partial v_{\theta g}}{\partial\theta}+\frac{v_z}{r}]-\frac{2}{3}\mu(\nabla.v) \qquad (3.31)$$

The angular component terms are to be neglected and applying explicit method with central and forward difference technique.

Now the L.H.S.

$$=> (\varepsilon_g\rho_g)_{i,j}^{t}\ \frac{\left(V_{rg}{}^{t+\Delta t}{}_{(i,j)}-V_{rg}{}^{t}{}_{(i,j)}\right)}{\Delta t}+\left(\frac{\varepsilon_g\rho_g V_{rg}{}^{t}}{r}\right)_{(i,j)}\frac{\left(V_{rg}{}^{t}{}_{(i,j)}-V_{rg}{}^{t}{}_{(i-1,j)}\right)}{\Delta r}+$$

$$(\varepsilon_g\rho_g V_{zg})_{i,j}^{t}\ \frac{\left(V_{rg}{}^{t}{}_{(i,j)}-V_{rg}{}^{t}{}_{(i,j)}\right)}{\Delta z}$$

And R.H.S

$$=> \frac{1}{r}\ \frac{\partial\left(2\mu r\varepsilon_g\frac{\partial V_{rg}}{\partial r}\right)}{\partial r}+\frac{\partial\left(\mu\varepsilon_g\left[\frac{\partial V_{rg}}{\partial z}+\frac{\partial V_{zg}}{\partial r}\right]\right)}{\partial r}-\ 2\,\frac{\mu\varepsilon_g V_{rg}}{r}-\varepsilon_g\nabla P_g$$

$$+F_{gs}(V_s-V_g)+\ \varepsilon_g\rho_g g$$

After expansion this can be written as follows.

$$=>\frac{2\mu}{r}\left[\varepsilon_g\frac{\partial V_{rg}}{\partial r}+r\varepsilon_g\frac{\partial^2 V_{rg}}{\partial r^2}+r\frac{\partial V_{rg}}{\partial r}\frac{\partial\varepsilon_g}{\partial r}\right]+\mu\left[\frac{\partial V_{rg}}{\partial z}\frac{\partial\varepsilon_g}{\partial z}+\frac{\partial V_{zg}}{\partial r}\frac{\partial\varepsilon_g}{\partial z}+\right.$$

$$\left.\varepsilon_g\frac{\partial^2 V_{rg}}{\partial z^2}+\varepsilon_g\frac{\partial^2 V_{zg}}{\partial z\,\partial r}\right]-2\varepsilon_g\mu\frac{V_{rg}}{r}-\varepsilon_g\frac{\partial P_g}{\partial r}+F_{gs}\left(V_s-V_g\right)+\varepsilon_g\rho_g g$$

$$=>\frac{2\mu}{r}\varepsilon_g\frac{\partial V_{rg}}{\partial r}+2\mu\varepsilon_g\frac{\partial^2 V_{rg}}{\partial r^2}+2\mu\frac{\partial V_{rg}}{\partial r}\frac{\partial\varepsilon_g}{\partial r}+\mu\frac{\partial V_{rg}}{\partial z}\frac{\partial\varepsilon_g}{\partial z}+\mu\frac{\partial V_{zg}}{\partial r}\frac{\partial\varepsilon_g}{\partial z}+$$

$$\mu\varepsilon_g\frac{\partial^2 V_{rg}}{\partial z^2}+\mu\frac{\partial^2 V_{zg}}{\partial z\,\partial r}-2\varepsilon_g\mu\frac{V_{rg}}{r}-\varepsilon_g\frac{\partial P_g}{\partial r}+F_{gs}\left(V_s-V_g\right)+\varepsilon_g\rho_g g$$

$$-\frac{2}{3r}\frac{\partial}{\partial r}\{\mu r\varepsilon_g(\nabla.V)\}+\frac{2\mu}{3r}\varepsilon_g(\nabla.V)$$

(3.32)

Now the discretized form of the above equation is

$$(2\mu\,\frac{\varepsilon_g}{r})_{i,j}^t\,\frac{\left(Vrg^t{}_{(i+1,j)}-Vrg^t{}_{(i-1,j)}\right)}{2\Delta r}+(2\mu\varepsilon_g\,)_{i,j}^t\,\frac{\left(Vrg^t{}_{(i+1,j)}-Vrg^t{}_{(i,j)}+Vrg^t{}_{(i-1,j)}\right)}{\nabla r^2}+$$

$$(2\mu\,)_{i,j}^t\,\frac{\left(Vrg^t{}_{(i+1,j)}-Vrg^t{}_{(i-1,j)}\right)}{2\Delta r}\frac{\left(\varepsilon g^t{}_{(i+1,j)}-\varepsilon g^t{}_{(i-1,j)}\right)}{2\Delta r}+$$

$$(\mu\,)_{i,j}^t\,\frac{\left(Vrg^t{}_{(i,j+1)}-Vrg^t{}_{(i,j-1)}\right)}{2\Delta z}\frac{\left(\varepsilon g^t{}_{(i,j+1)}-\varepsilon g^t{}_{(i,j-1)}\right)}{2\Delta z}+(\mu\,)_{i,j}^t\,\frac{\left(\varepsilon g^t{}_{(i,j+1)}-\varepsilon g^t{}_{(i,j-1)}\right)}{2\Delta z}$$

$$\frac{\left(Vzg^t{}_{(i+1,j)}-Vzg^t{}_{(i-1,j)}\right)}{2\Delta r}+(\mu\varepsilon_g\,)_{i,j}^t\,\frac{\left(Vrg^t{}_{(i,j+1)}-Vrg^t{}_{(i,j)}+Vrg^t{}_{(i,j-1)}\right)}{\nabla z^2}+$$

$$(\mu\,\frac{\varepsilon_g}{2\nabla r})_{i,j}^t\,\frac{\left(Vzg^t{}_{(i+1,j+1)}-Vzg^t{}_{(i+1,j-1)}-Vzg^t{}_{(i-1,j+1)}-Vzg^t{}_{(i-1,j-1)}\right)}{2\Delta z}-2(\varepsilon_g\mu\frac{Vrg}{r})_{i,j}^t-$$

$$(\varepsilon_g\,)_{i,j}^t\,\frac{\left(Prg^t{}_{(i,j+1)}-Prg^t{}_{(i,j-1)}\right)}{\Delta r}+(\varepsilon_g\rho_g\,g)_{i,j}^t+\{F_{gs}\left(V_{rs}-V_{rg}\right)\}_{i,j}^t+$$

$$(\frac{2}{3}\mu)_{i,j}^{t}\{ \frac{\left(\varepsilon_g{}^t{}_{(i+1,j)}-\varepsilon_g{}^t{}_{(i-1,j)}\right)}{2\Delta r}\frac{\left(V_{rg}{}^t{}_{(i+1,j)}-V_{rg}{}^t{}_{(i-1,j)}\right)}{2\Delta r}+(\frac{V_{rg}}{r})_{i,j}^{t}\frac{\left(\varepsilon_g{}^t{}_{(i+1,j)}-\varepsilon_g{}^t{}_{(i-1,j)}\right)}{2\Delta r}$$

$$+(2\frac{\varepsilon_g}{r})_{i,j}^{t}\frac{\left(V_{rg}{}^t{}_{(i+1,j)}-V_{rg}{}^t{}_{(i-1,j)}\right)}{2\Delta r}+(\varepsilon_g)_{i,j}^{t}\frac{\left(V_{rg}{}^t{}_{(i+1,j)}-V_{rg}{}^t{}_{(i,j)}+V_{rg}{}^t{}_{(i-1,j)}\right)}{\nabla r^2}+$$

$$(\frac{\varepsilon_g}{r})_{i,j}^{t}\frac{\left(V_{zg}{}^t{}_{(i,j+1)}-V_{zg}{}^t{}_{(i,j-1)}\right)}{2\Delta z}+\frac{\left(\varepsilon_g{}^t{}_{(i+1,j)}-\varepsilon_g{}^t{}_{(i-1,j)}\right)}{2\Delta r}\frac{\left(V_{zg}{}^t{}_{(i,j+1)}-V_{zg}{}^t{}_{(i,j-1)}\right)}{2\Delta z}+$$

$$(\varepsilon_g)_{i,j}^{t}\frac{\left(V_{zg}{}^t{}_{(i+1,j+1)}-V_{zg}{}^t{}_{(i+1,j-1)}-V_{zg}{}^t{}_{(i-1,j+1)}-V_{zg}{}^t{}_{(i-1,j-1)}\right)}{4\Delta r\Delta z}\}+$$

$$\{\left(\frac{V_{rg}}{r^2}\right)_{i,j}^{t}+\frac{1}{r}\frac{\left(V_{rg}{}^t{}_{(i+1,j)}-V_{rg}{}^t{}_{(i-1,j)}\right)}{2\Delta r}+\frac{1}{r}\frac{\left(V_{zg}{}^t{}_{(i,j+1)}-V_{zg}{}^t{}_{(i,j-1)}\right)}{2\Delta z}\}(\frac{2}{3}\varepsilon_g\mu)_{i,j}^{t}$$

(3.33)

At r =0, applying L'Hospital rule

L.H.S

$$=>(\varepsilon_g\rho_g)_{i,j}^{t}\frac{\left(V_{rg}{}^{t+\Delta t}{}_{(i,j)}-V_{rg}{}^t{}_{(i,j)}\right)}{\Delta t}+(\varepsilon_g\rho_g)_{i,j}^{t}\frac{\left(V_{rg}{}^t{}_{(i,j)}-V_{rg}{}^t{}_{(i-1,j)}\right)^2}{\Delta r}+$$

$$(\varepsilon_g\rho_g V_{zg})_{i,j}^{t}\frac{\left(V_{rg}{}^t{}_{(i,j)}-V_{rg}{}^t{}_{(i,j)}\right)}{\Delta z}$$

R.H.S

$$(\mu\frac{\varepsilon_g}{\Delta r})_{i,j}^{t}\frac{\left(V_{rg}{}^t{}_{(i+2,j)}-2V_{rg}{}^t{}_{(i,j)}+V_{rg}{}^t{}_{(i-2,j)}\right)}{2\Delta r}+$$

$$(2\mu\varepsilon_g)_{i,j}^{t}\frac{\left(V_{rg}{}^t{}_{(i+1,j)}-2V_{rg}{}^t{}_{(i,j)}+V_{rg}{}^t{}_{(i-1,j)}\right)}{\nabla r^2}+$$

$$(2\mu)_{i,j}^{t}\frac{\left(V_{rg}{}^t{}_{(i+1,j)}-V_{rg}{}^t{}_{(i-1,j)}\right)}{2\Delta r}\frac{\left(\varepsilon_g{}^t{}_{(i+1,j)}-\varepsilon_g{}^t{}_{(i-1,j)}\right)}{2\Delta r}+$$

$$(\mu)_{i,j}^{t}\ \frac{\left(V_{rg}{}^{t}{}_{(i,j+1)}-V_{rg}{}^{t}{}_{(i,j-1)}\right)}{2\Delta z}\frac{\left(\varepsilon_{g}{}^{t}{}_{(i,j+1)}-\varepsilon_{g}{}^{t}{}_{(i,j-1)}\right)}{2\Delta z}+\ (\mu)_{i,j}^{t}\ \frac{\left(\varepsilon_{g}{}^{t}{}_{(i,j+1)}-\varepsilon_{g}{}^{t}{}_{(i,j-1)}\right)}{2\Delta z}$$

$$\frac{\left(V_{zg}{}^{t}{}_{(i+1,j)}-V_{zg}{}^{t}{}_{(i-1,j)}\right)}{2\Delta r}\ +(\mu\varepsilon_{g})_{i,j}^{t}\ \frac{\left(V_{rg}{}^{t}{}_{(i,j+1)}-V_{rg}{}^{t}{}_{(i,j)}+V_{rg}{}^{t}{}_{(i,j-1)}\right)}{\nabla z^{2}}+$$

$$(\mu\ \frac{\varepsilon_g}{2\nabla r})_{i,j}^{t}\ \frac{\left(V_{zg}{}^{t}{}_{(i+1,j+1)}-V_{zg}{}^{t}{}_{(i+1,j-1)}-V_{zg}{}^{t}{}_{(i-1,j+1)}-V_{zg}{}^{t}{}_{(i-1,j-1)}\right)}{2\Delta z}-2(\varepsilon_{g}\mu\frac{v_{rg}}{r})_{i,j}^{t}\ -$$

$$(\varepsilon_{g})_{i,j}^{t}\ \frac{\left(P_{rg}{}^{t}{}_{(i,j+1)}-P_{rg}{}^{t}{}_{(i,j-1)}\right)}{\Delta r}+(\varepsilon_{g}\mu)_{i,j}^{t}\ \frac{\left(V_{rg}{}^{t}{}_{(i+1,j)}-V_{rg}{}^{t}{}_{(i-1,j)}\right)}{2\Delta r}+$$

$$\{F_{gs}\ (V_{rs}-V_{rg})\}_{i,j}^{t}\ +(\frac{2}{3}\mu)_{i,j}^{t}\{\ \frac{\left(\varepsilon_{g}{}^{t}{}_{(i+1,j)}-\varepsilon_{g}{}^{t}{}_{(i-1,j)}\right)}{2\Delta r}\frac{\left(V_{rg}{}^{t}{}_{(i+1,j)}-V_{rg}{}^{t}{}_{(i-1,j)}\right)}{2\Delta r}+$$

$$\frac{\left(V_{rg}{}^{t}{}_{(i+1,j)}-V_{rg}{}^{t}{}_{(i-1,j)}\right)}{2\Delta r}\frac{\left(\varepsilon_{g}{}^{t}{}_{(i+1,j)}-\varepsilon_{g}{}^{t}{}_{(i-1,j)}\right)}{2\Delta r}+(\varepsilon_{g})_{i,j}^{t}\ \frac{\left(V_{rg}{}^{t}{}_{(i+2,j)}-V_{rg}{}^{t}{}_{(i,j)}+V_{rg}{}^{t}{}_{(i-2,j)}\right)}{2\nabla r^{2}}+$$

$$(\varepsilon_{g})_{i,j}^{t}\ \frac{\left(V_{rg}{}^{t}{}_{(i+1,j)}-V_{rg}{}^{t}{}_{(i,j)}+V_{rg}{}^{t}{}_{(i-1,j)}\right)}{\nabla r^{2}}+$$

$$+\frac{\left(\varepsilon_{g}{}^{t}{}_{(i+1,j)}-\varepsilon_{g}{}^{t}{}_{(i-1,j)}\right)}{2\Delta r}\ \frac{\left(V_{zg}{}^{t}{}_{(i,j+1)}-V_{zg}{}^{t}{}_{(i,j-1)}\right)}{2\Delta z}+$$

$$(\varepsilon_{g})_{i,j}^{t}\ \frac{\left(V_{zg}{}^{t}{}_{(i+1,j+1)}-\ V_{zg}{}^{t}{}_{(i+1,j-1)}-V_{zg}{}^{t}{}_{(i-1,j+1)}-\ V_{zg}{}^{t}{}_{(i-1,j-1)}\right)}{2\Delta r\Delta z}\}+$$

$$\{\frac{\left(V_{rg}{}^{t}{}_{(i+2,j)}-V_{rg}{}^{t}{}_{(i,j)}+V_{rg}{}^{t}{}_{(i-2,j)}\right)}{(4\Delta r)(2\Delta r)}+\frac{\left(V_{rg}{}^{t}{}_{(i+2,j)}-V_{rg}{}^{t}{}_{(i,j)}+V_{rg}{}^{t}{}_{(i-2,j)}\right)}{(2\Delta r)(2\Delta r)}+$$

$$\frac{\left(V_{zg}{}^{t}{}_{(i+1,j+1)}-V_{zg}{}^{t}{}_{(i+1,j-1)}-V_{zg}{}^{t}{}_{(i-1,j+1)}-V_{zg}{}^{t}{}_{(i-1,j-1)}\right)}{2\Delta r.2\Delta z}\}\ (\frac{2}{3}\varepsilon_{g}\mu)_{i,j}^{t}$$

3.10 For the vertical component

Z-momentum balance equation

$$\varepsilon_g \rho_g \frac{\partial V_{zg}}{\partial t} + \varepsilon_g \rho_g V_{rg} \frac{\partial V_{zg}}{\partial r} + \varepsilon_g \rho_g V_{zg} \frac{\partial V_{zg}}{\partial z} = \frac{1}{r} \frac{\partial (r\, \varepsilon_g \tau_{rz})}{\partial r} +$$

$$\frac{1}{r} \frac{\partial (\tau_{\theta z} \varepsilon_g)}{\partial \theta} + \frac{\partial (\varepsilon_g \tau_{zz})}{\partial z} - \varepsilon_g \frac{\partial \rho_g}{\partial z} + F_{gs} \left(V_s - V_g \right) + \varepsilon_g \rho_g g$$

$$\tau_{r_z} = \mu \left[\frac{\partial V_{rg}}{\partial z} + \frac{\partial V_{zg}}{\partial r} \right], \quad \tau_{z_z} = 2\mu \frac{\partial V_{rg}}{\partial z} - \frac{2}{3} \mu (\nabla . V)$$

(3.34)

In the equation the angular components are neglected and applying the explicit scheme with central and forward different method

L.H.S

$$= (\varepsilon_g \rho_g)^t_{(i,j)} \frac{({V_{zg}}^{(t+\Delta t)}_{(i,j)} - {V_{zg}}^{(t)}_{(i,j)})}{\Delta t} + (\varepsilon_g V_r \rho_g)^t_{(i,j)} \frac{({V_{zg}}^{(t)}_{(i,j)} - {V_{zg}}^{(t)}_{(i-1,j)})}{\Delta r} + (\varepsilon_g V_z \rho_g)^t_{(i,j)} \frac{({V_{zg}}^{(t)}_{(i,j)} - {V_{zg}}^{(t)}_{(i-1,j)})}{\Delta z}$$

R.H.S

$$= \frac{\mu}{r} \left[\frac{\partial \left(r\, \varepsilon_g \frac{\partial V_{rg}}{\partial z} \right)}{\partial r} + \frac{\partial \left(r\, \varepsilon_g \frac{\partial V_{zg}}{\partial r} \right)}{\partial r} + \frac{\partial \left(2\mu\, \varepsilon_g \frac{\partial V_{zg}}{\partial z} \right)}{\partial r} - \varepsilon_g \frac{\partial \rho_g}{\partial z} + F_{gs} \left(V_s - V_g \right) + \varepsilon_g \rho_g g - \frac{\partial (\varepsilon_g \frac{2}{3} \mu (\nabla . V)}{\partial z} \right]$$

Atr=0;L.H.S

$$= (\varepsilon_g \rho_g)^t_{(i,j)} \frac{({V_{zg}}^{(t+\Delta t)}_{(i,j)} - {V_{zg}}^{(t)}_{(i,j)})}{\Delta t} + (\varepsilon_g V_r \rho_g)^t_{(i,j)} \frac{({V_{zg}}^{(t)}_{(i,j)} - {V_{zg}}^{(t)}_{(i-1,j)})}{\Delta r} + (\varepsilon_g V_z \rho_g)^t_{(i,j)} \frac{({V_{zg}}^{(t)}_{(i,j)} - {V_{zg}}^{(t)}_{(i-1,j)})}{\Delta z}$$

R.H.S

$$= \frac{\mu}{r}\left[\frac{\partial\left(r\ \varepsilon_g \frac{\partial V_{rg}}{\partial z}\right)}{\partial r} + \frac{\partial\left(r\ \varepsilon_g \frac{\partial V_{zg}}{\partial r}\right)}{\partial r} + \frac{\partial\left(2\mu\ \varepsilon_g \frac{\partial V_{zg}}{\partial z}\right)}{\partial r} - \varepsilon_g \frac{\partial \rho_g}{\partial z} + F_{gs}\left(V_s - V_g\right) + \varepsilon_g \rho_g g - \frac{\partial(\varepsilon_g \frac{2}{3}\mu(\nabla . V)}{\partial z} \right]$$

$$\Rightarrow \frac{\mu}{r}\ [[\ r\frac{\partial \varepsilon_g}{\partial r}\ \frac{\partial V_{rg}}{\partial z} + \varepsilon_g \frac{\partial V_{rg}}{\partial z} + \ r\varepsilon_g \frac{\partial^2 V_{rg}}{\partial z \partial r}\ ] + \ [\mu\varepsilon_g \frac{\partial^2 V_{rg}}{\partial z\partial r} + \frac{\mu}{r}\varepsilon_g \frac{\partial V_{rg}}{\partial r} + \mu\frac{\partial \varepsilon_g}{\partial r}\ \frac{\partial V_{zg}}{\partial r} + \ \mu\varepsilon_g \frac{\partial^2 V_{rg}}{\partial r^2}] + 2\mu\varepsilon_g \frac{\partial^2 V_{rg}}{\partial r^2} - \varepsilon_g \frac{\partial \rho_g}{\partial z} + F_{gs}\left(V_s - V_g\right) + \varepsilon_g\rho_g g - \frac{\partial(\varepsilon_g \frac{2}{3}\mu(\nabla . V)}{\partial z}$$

$$\mu_{(i,j)}\left(\frac{{\varepsilon_g}^{t}{}_{(i+1,j)} - {\varepsilon_g}^{t}{}_{(i-1,j)}}{2\Delta r}\right)\left(\frac{{V_{rg}}^{t}{}_{(i,j+1)} - {V_{rg}}^{t}{}_{(i,j-1)}}{2\Delta z}\right) + \mu{\varepsilon_g}^{t}{}_{(i,j)}\left(\frac{{V_{zg}}^{t}{}_{(i+1,j)} - 2{V_{zg}}^{t}{}_{(i,j)} + {V_{zg}}^{t}{}_{(i-1,j)}}{(\Delta r)^2}\right) +$$

$$\frac{\mu{\varepsilon_g}^{t}_{(i,j)}}{2\Delta r}\left[\frac{{V_{rg}}^{t}{}_{(i+1,j+1)} - {V_{rg}}^{t}{}_{(i+1,j-1)}}{2\Delta z} - \frac{{V_{rg}}^{t}{}_{(i-1,j+1)} - {V_{rg}}^{t}{}_{(i-1,j-1)}}{2\Delta z}\right] + \mu{\varepsilon_g}^{t}_{(i,j)}\left[\frac{{V_{rg}}^{t}{}_{(i+1,j+1)} - {V_{rg}}^{t}{}_{(i+1,j-1)} - {V_{rg}}^{t}{}_{(i-1,j+1)} - {V_{rg}}^{t}{}_{(i-1,j-1)}}{2\Delta z\ 2\Delta r}\right] +$$

$$(\varepsilon_g\mu)^{t}_{i,j}\ \frac{\left({V_{zg}}^{t}{}_{(i+2,j)} - 2{V_{zg}}^{t}{}_{(i,j)} + {V_{rg}}^{t}{}_{(i-2,j)}\right)}{\Delta r . 2\Delta z}$$

$$+ 2\mu{\varepsilon_g}^{t}{}_{(i,j)}\left(\frac{{V_{zg}}^{t}{}_{(i,j+1)} - 2{V_{zg}}^{t}{}_{(i,j)} + {V_{zg}}^{t}{}_{(i,j-1)}}{(\Delta z)^2}\right) + F_{gs}\left(V_s - V_g\right) +$$

$$\varepsilon_g \rho_g g\,^{t}_{(i,j)} + 0.3\varepsilon_g{}^{t}_{(i,j)} -$$

$$\left(\frac{2}{3}\mu\right)^{t}_{i,j} \{ \frac{\left(\varepsilon_g{}^{t}_{(i,j+1)} - \varepsilon_g{}^{t}_{(i,j-1)}\right)}{2\Delta z} \frac{\left(V_{rg}{}^{t}_{(i+1,j)} - V_{rg}{}^{t}_{(i-1,j)}\right)}{2\Delta r} +$$

$$(\varepsilon_g)^{t}_{i,j} \; \frac{\left(V_{rg}{}^{t}_{(i+1,j+1)} - V_{rg}{}^{t}_{(i+1,j-1)} - V_{rg}{}^{t}_{(i-1,j+1)} - V_{rg}{}^{t}_{(i-1,j-1)}\right)}{2\Delta r.2\Delta z} +$$

$$\frac{\left(\varepsilon_g{}^{t}_{(i,j+1)} - \varepsilon_g{}^{t}_{(i,j-1)}\right)}{2\Delta z} \frac{\left(V_{zg}{}^{t}_{(i,j+1)} - V_{zg}{}^{t}_{(i,j-1)}\right)}{2\Delta z} +$$

$$(\varepsilon_g)^{t}_{i,j} \; \frac{\left(V_{rg}{}^{t}_{(i+1,j+1)} - V_{rg}{}^{t}_{(i+1,j-1)} - V_{rg}{}^{t}_{(i-1,j+1)} - V_{rg}{}^{t}_{(i-1,j-1)}\right)}{2\Delta r.2\Delta z} +$$

$$\left(\frac{\varepsilon_g}{r}\right)^{t}_{i,j} \; \frac{\left(V_{rg}{}^{t}_{(i,j+1)} - V_{rg}{}^{t}_{(i,j-1)}\right)}{2\Delta z} +$$

$$(\varepsilon_g)^{t}_{i,j} \; \frac{\left(V_{zg}{}^{t}_{(i,j+1)} - 2V_{zg}{}^{t}_{(i,j)} + V_{rg}{}^{t}_{(i,j-1)}\right)}{\Delta z^2}$$

After discretizing the above governing equations these can be changed into a numerical form for easy applications such as for the computation of different velocity profiles, void fraction etc. for the systems between the boundary conditions.

Sample flow diagram for computational solution of an equation is shown below (Fig. 3.1).

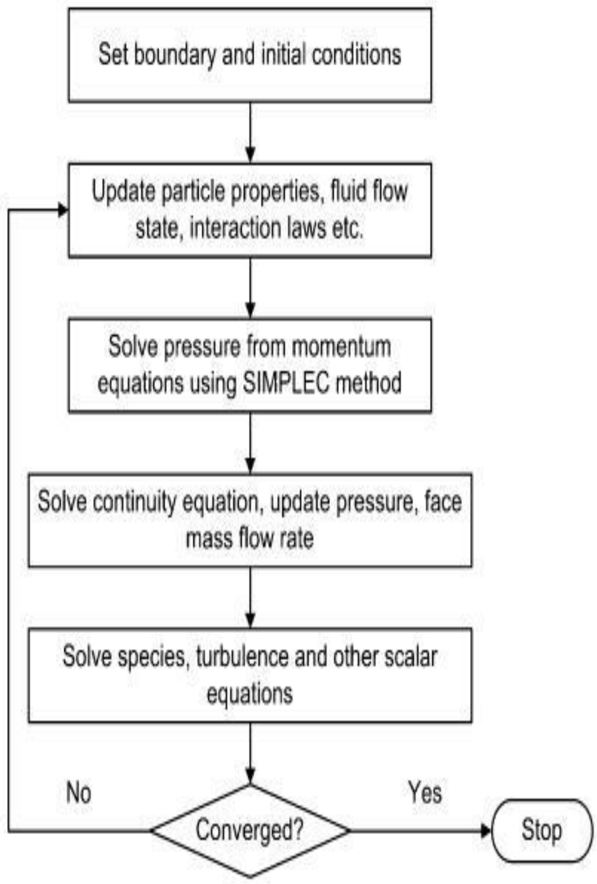


Fig.3.1 Flow diagram for the computational treatment of the equations.

Chapter 4

Experimentation

The experimental part of the study is described below within different headings.

4.1 EXPERIMENTAL PROCEDURE

4.1.1 The experiment has been carried out for the study of fluidization behavior of spouted bed. Known amount of materials were taken and four sizes of orifice spouts were made by thick strong card board. The prepared distributor was sandwiched between the flanges and made air tight with the use of gasket. The screen of very fine size was put to prevent the backflow of bed materials below the distributor. The experiments were carried out by changing the different system parameters as discussed in scope of the experiment (Table 4.1). The bed expanded bed heights and bed manometer readings were noted down at different flow rates of the supplied fluid.

Table 4.1 Parameters variations shown in table for correlation development

Sl. No.	$d_p \times 10^3$,m	Hs,m	$\rho_s \times 10^{-3}$, kg/m^3	U_o/U_{ms}	d_i, m
1	4.66	0.08	2.227	1.4	0.01
2	3.93	0.08	2.227	1.4	0.01
3	3.40	0.08	2.227	1.4	0.01
4	2.64	0.08	2.227	1.4	0.01
5	3.93	0.04	2.227	1.4	0.01
6	3.93	0.06	2.227	1.4	0.01
7	3.93	0.08	2.227	1.4	0.01
8	3.93	0.10	2.227	1.4	0.01
9	3.93	0.08	2.227	1.4	0.01
10	3.93	0.08	2.805	1.4	0.01
11	3.93	0.08	1.845	1.4	0.01
12	3.93	0.08	1.601	1.4	0.01
13	3.93	0.08	2.227	1.2	0.01
14	3.93	0.08	2.227	1.3	0.01
15	3.93	0.08	2.227	1.4	0.01
16	3.93	0.08	2.227	1.5	0.01
17	3.93	0.08	2.227	1.4	0.01
18	3.93	0.08	2.227	1.4	0.013
19	3.93	0.08	2.227	1.4	0.015
20	3.93	0.08	2.227	1.4	0.02

4.2 Particle density determination. An empty specific gravity bottle is taken and weighed. Then it is filled with water and again weighed. Some amount of glass beads of particular size are taken and weighed. Then glass beads are taken in the empty specific gravity bottle and the remaining space is filled with water. Then it is again weighed. Density of glass bead is calculated by water displacement method. This procedure is repeated for different sizes. Then average density of Glass bead, Dolomite, Coal and Brick samples were found out.

4.3 Particle Size Determination.

Glass beads where screened separated in different size but for determination of equivalent diameter of dolomite, coal and brick used. First of all the bigger samples were crushed and sieved with -4+6 screen size and the 100 particles of the samples where deepen in to a measuring cylinder. The water already taken was 10ml and sample was put the volume raised by the addition of material is measured, the volume increased was measured and that volume was divided by 100, now this volume is equal to the equivalent one particle sample and its diameter was calculated 3.93mm.

And in the second method the screened material's size was take as the average particle size and multiplied by the sphericity. The sphericity of particles was taken from the Book Mc-Cabe Smith. Unit Operations of Chemical Engineering. Where, for the sand particles and coal granular having 0.73 to 0.8 was given and also for the Dolomite it was assumed 0.73.

4.4 COMPONENTS OF EXPERIMENTAL SET-UP

The experimental set-up consists primarily of the following components

4.4.1 Air Compressor:

It is a multistage air compressor of sufficient capacity 25kgf/cm^2.

4.4.2 Air Accumulator:

It is a horizontal cylinder used for storing the compressed air from compressor. There is one G.I. pipe inlet to the accumulator and one by-pass from one end of the cylinder. The exit line is also a G.I. pipe taken from the central part of the cylinder. The purpose of using the air accumulator in the line is to dampen the pressure fluctuations. The accumulator is fitted with a pressure gauge. The operating pressure in the cylinder is kept at 20psig.

4.4.3 Pressure Gauge:

A pressure gauge in the required range (1-50psig) is fitted in the line for measuring the working pressure.

4.4.4 Rotameter:

A Rotameter is used in the line for measuring the flow rate of the air used as fluidizing medium. Its measuring capacity was 0 to 120m^3/hr

4.4.5 Air Calming Section

This is an important component of the experimental set-up. It consists of a cylindrical portion (4.5cm id. and 7.5cm length) followed by a conical bottom. The cone angle is about 35-40^o. The larger side is of 45mm id. and the smaller of 12mm id., the height of the cone being 6.5cm. The cone is brazed with G.I. flange of 11.4cm O.D. The central bore of the flange is also of 45 mm dia. The cone is made of ordinary G.I. sheet. The inside hollow space of the distributor is filled with 3mm dia. spherical glass beads for uniform distribution of air. The beads are supported over a coarse screen at the bottom.

4.4.5 Air Distributer:

In this experiment the distributer used was of the thick(4mm) card board which was so strong that not bending with air pressure and was easy to make hole in this of different sizes during the experiment.

4.4.6 Fluidizer:

The fluidizer consists of a 5cm id. and 100cm length transparent Perspex column with one ends fixed to Perspex flange. The flange have 4 bolt holes of ¼" dia and of 5/16" thickness. Two pressure tapings are provided for noting the bed pressure drop. An 80 mesh screen is provided between the lower flange of the fluidizer and the conical air distributor.

4.4.7 Valves:

A globe valve of ½ inch ID is provided in the by-pass line for sudden release of the line pressure. A gate valve of 1/2 inch ID is provided in the line just before rotameter to control the flow rate of air to the fluidizing bed.

4.4.8 Manometer Panel Board:

One set of manometer is arranged in this panel board to measure the bed pressure drop. Mercury was used as the manometric liquid and its density is 13600kg/m^3.

4.4.9 Silica Gel Chamber

A silica gel tower is used for absorbing the moisture content of the air supply.

4.1 (a) Glass bead sample.

4.1(b) brick sample

4.1 (c) coal sample

4.1(d) dolomite sample

Fig. 4.1 Samples used for spouting.

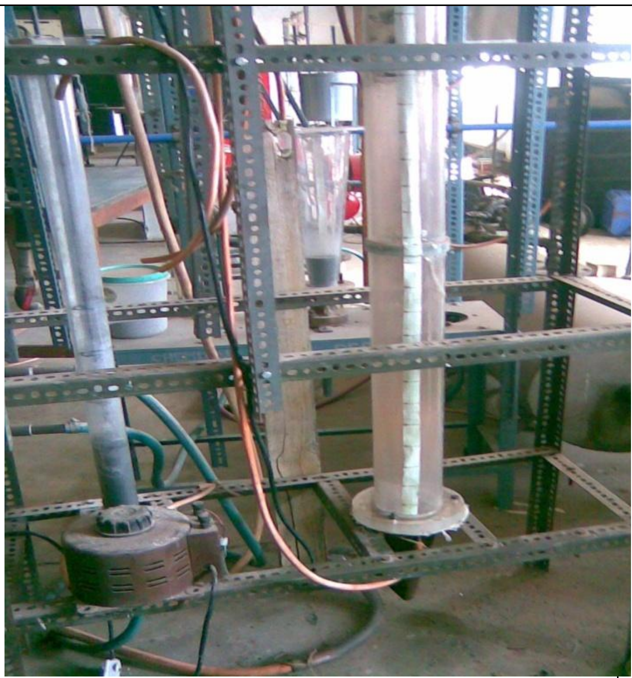


Fig. 4.2 (A).Spouting Chamber	**(B).Distributer**

4.2 (D).Compressure	**4.2 (D).Screen**

Fig. 4.2 Accessories and mountings used in the experimentation

4.5 Difficulties Associated With the Experiment

The following difficulties where faced during the experiment

a. spouting with very low orifice in the range of 4mm and below was not possible because of high pressure drop connections of rubber tube with air supply and manometers were detached because pressure was more than 20 time greater than from fluidization on same set up.
b. Due to breaking tendency of brick particle it was needed to change particles frequently.
c. For lighter density (coal, dolomite) particles elutriation was also a problem at high flow rate.
d. At the time of slugging the pressure variation was so heigh to that create problem to take readings.

The expanded bed height and the manometer reading were noted according to the varying flow rate with the following parameters tabulated below.

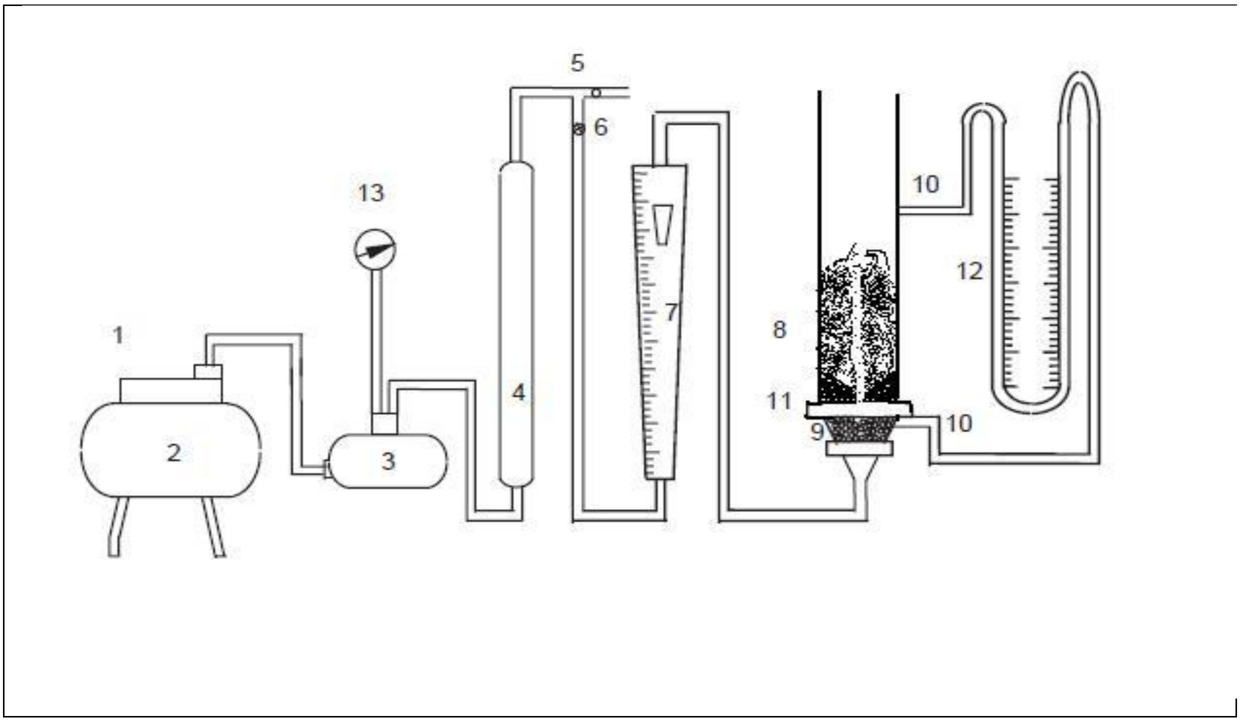


Fig. 4.3 Experimental Se-Up Arrangement

4.6 Experimental setup arrangement

1. Compressor
2. Receiver
3. Constant pressure tank
4. Silica gel tower
5. by pass valve
6. Line valve
7. Rotameter

8.spouting bed

9.calming section with glass bead packing

10. Pressure tapping

11.distributer

12. Manometer (mercury columns)

13.pressure gage

4.7 Setup specification:

1. Fluidizing cylinder used of height of 1and 1.25m material used for manufacturing was Perspex sheet.

2. Rotameter used was of range 0 to 120 m^3/hr

3. Compressor capacity 25kgf/cm^2

4 .calming section with glass bead packing had height 25 cm and 10cm respectively conical at angle of 20 to 25^o

5. Manometer (mercury columns) density of mercury 13600kg/m^3

6. Pressure gage measuring capacity 56kg/cm^2

Chapter 5

Results and Discussion

On the basis of experimental observations one can analyses the stability and termination of fountain for the spouted bed. The state of fluidization/slugging depends on various system parameters. With the increase in static bed height the spouting height decreases and the tendency indicates the instability of spouting with the increase of height. Thus one can conclude that the bed fluctuation starts and the state changes to the bad fluidization with high F.I. as shown in Table 5.2**.** It was observed that with increase in the bed height from 3 to 8cm the spouting stopped and fluidization started for the 4.65mm glass beads and the spouting was observed to be vanished between 8 to 10 cm bed heights. But the spouting heights also found to be affected by the particle sizes. Maximum spouting height is observed by the smallest particles. The bed slugging was found to be formed with the smaller particle sizes.

Effect of flow rate mostly on every size and density particles showed the same way of effect with the increase of flow rate the spout height increases but after a certain height the fluctuation started it is due to the penetration of air flow through annulus region. Generally at the lower bed height fluidization not started at any flow rate but at higher bed heights it takes place.

The pressure drop with the increase of flow rate increase in the condition of slugging for each and every particles, but before spouting the pressure drop fist increase then decrease up to some extent then becomes constant fig. 5.1.

With the increase in spout diameter the spouting height decreases continuously for a fixed flow rate and on increasing the bed height the spouting height decreases and after maximum spouting height fluctuation started.

By the mathematical modeling of the system velocity and voidage profiles were found and by these profiles one can easily observe that the with the increase of orifice diameter the minimum spouting velocity increases Fig.5.16. The void fraction of solid increases with increase in the bed height (Fig. 5.18).

On the basis of all the above observation and by the dimensionless analysis the correlation Expansion ratio and fluctuating index is determined. The developed correlation for fluctuation/expansion ratio and fluidization index can therefore be used for the industrial level over a wide range of parameters. The spouted behavior with different parameters gives the idea of energy conservation for various industries about which are of great concern in the present scenario

5.1 The Correlation for bed expansion ratio

$$R = 9*10^{10}[(delU/U_{ms})^{.437}*(H_s/D_c)^{-.275}*(d_i/D_c)^{.244}*(\rho_s/\rho_f)^{-3.21}*(d_p/D_c)^{-.38}] \quad (5.1)$$

5.2 The correlation for fluidization index

$$F.I = .985[(delU/U_{ms})^{.418}*(H_s/D_c)^{-1.00}*(d_i/D_c)^{-1.166}*(\rho_s/\rho_f)^{-3.71}*(d_p/D_c)^{-.89}] \quad (5.2)$$

The pressure drop with respect to superficial velocity for the spouting condition was found in the following way.

Table 5.1 Observed data for the superficial velocity and pressure drop for different samples

Dolomite sample		Glass sample		Coal sample		Brick sample	
V(m/sec)	ΔP(kp)	V(m/sec)	ΔP(kp)	V(m/sec)	ΔP(kp)	V(m/sec)	ΔP(kp)
0.15	2	0.25	2	1	0.2	2	0.5
0.3	4	0.5	4	2	0.3	3	0.75
0.75	8	0.7	6	3	0.75	4	1
1.25	12	1.15	9.2	5	1	5	1.1
1.75	16	1.8	14	4	1.5	3.6	1.25
2.1	17.4	2.51	11	4	1.6	3.2	1.35
2.15	16	3	11	4	1.5	3.2	1.5
2.25	14	3.4	11	5	1.4	-	-

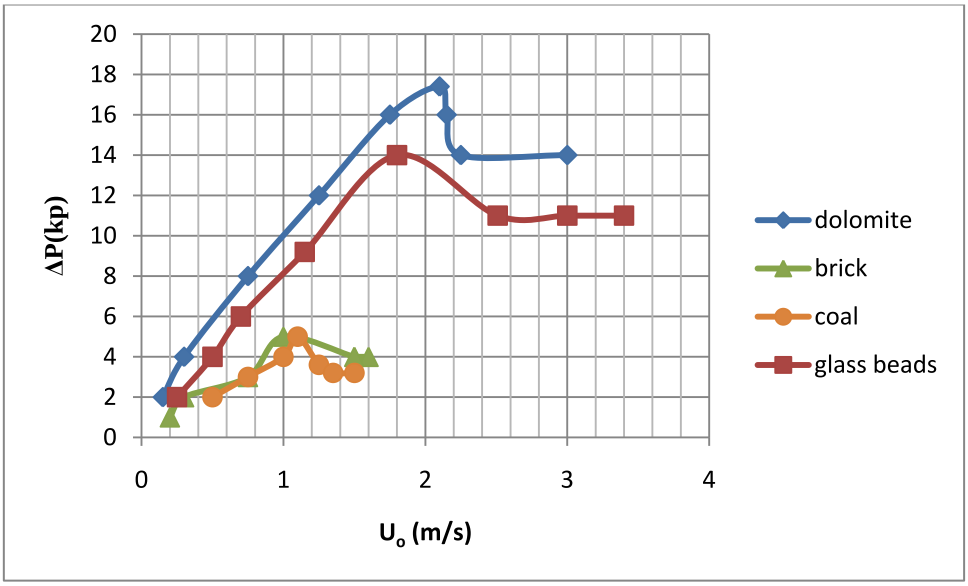


Figure 5.1 Plot of pressure drop vs. superficial velocity for different materials

Table 5.2 Variation of the spouting height with change in particle sizes

Glass beads d_p=4.65mm		**Glass beds d_p=2.64mm**	
H_{max}.(cm) spout height	H_s(cm) Bead height	H_{max}.(cm) Spout height	H_s(cm) Bead height
Spouting bed		Spouting bed	
22	3	29	3
17	5	26	4
9	8	22	6
		16	8
Fluidizing/slugging bed		Fluidizing/slugging bed	
16	10	11	9
23	12	-	-
27	13	13	10
-	-	18	12
-	-	30	13

Table.5.3 Variation of the spouting height with change in particle sizes

Glass beads d_p=3.93mm		Glass beads d_p=3.4mm	
H_{max}.(cm) spout height	H_s(cm) Bead height	H_{max}.(cm) Spout height	H_s(cm) Bead height
Spouting bed		Spouting bed	
21	4	24	3
15	6	22	4
9	8	10	8
Fluidization/slugging		Fluidization/slugging	
14	8	12	8
18	10	18	10
24	11	26	11

H_{max} represents the maximum fountain height at spouting condition and maximum bed height attained at fluidization condition in the following figures.

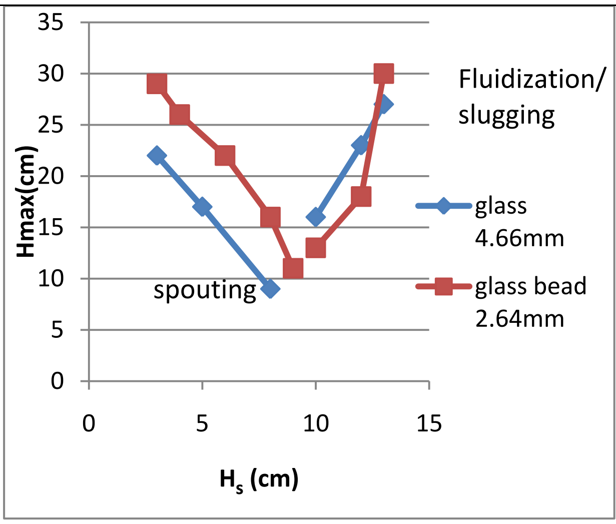


Fig. 5.2(a) Maximum fountain height H_{max} vs H_s graph for 4.66mm and 2.64mm

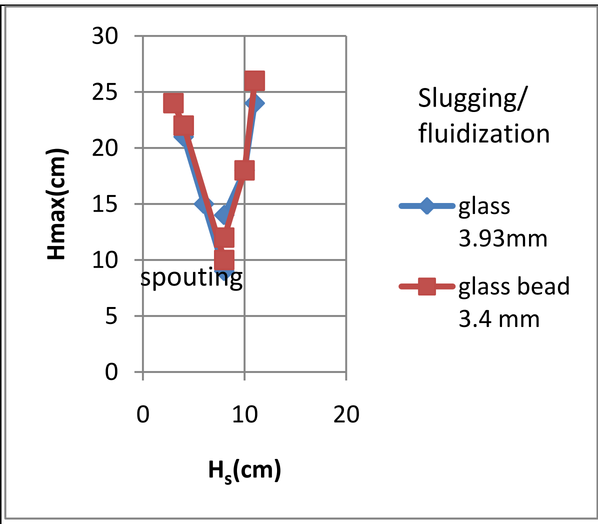


Fig. 5.2(b) for the 3.93 and 3.4mm glass beads

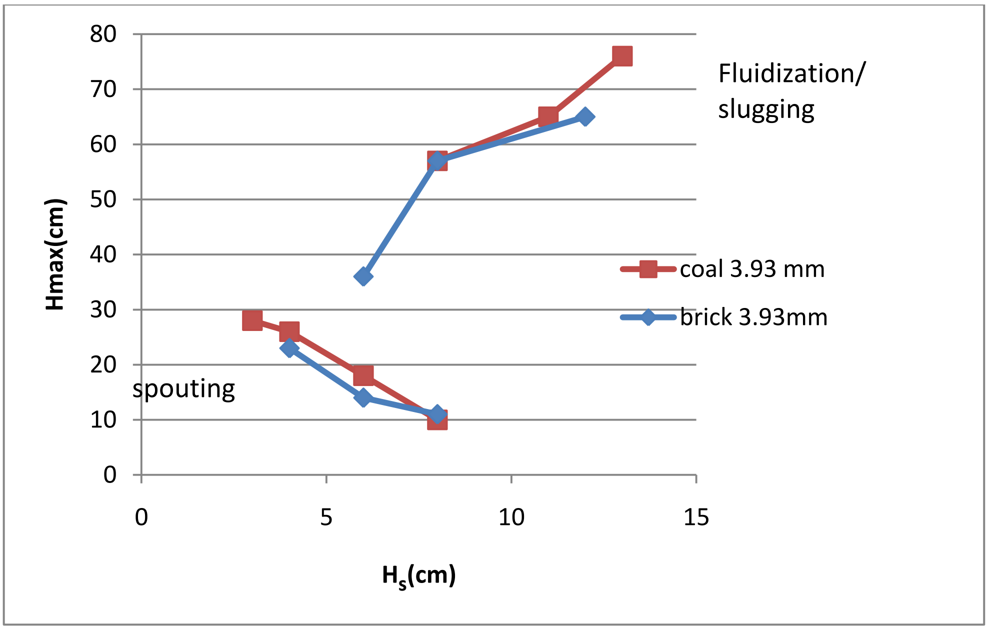


Fig. 5.3 Maximum fountain height vs. static bed height for Brick And Coal Particles.

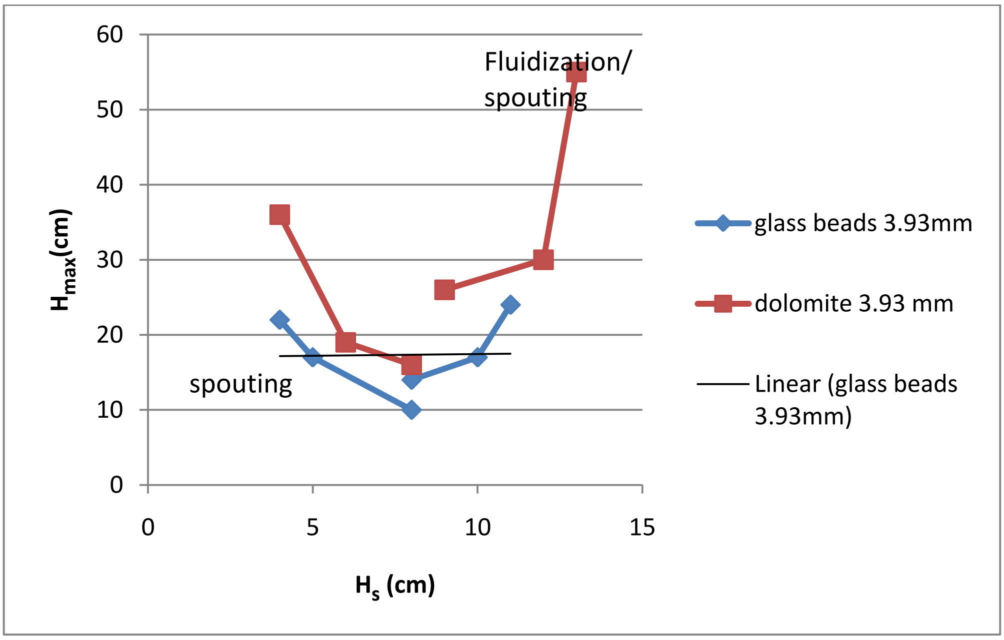


Fig. 5.4 Maximum fountain height vs. static bed height for dolomite and glass beads.

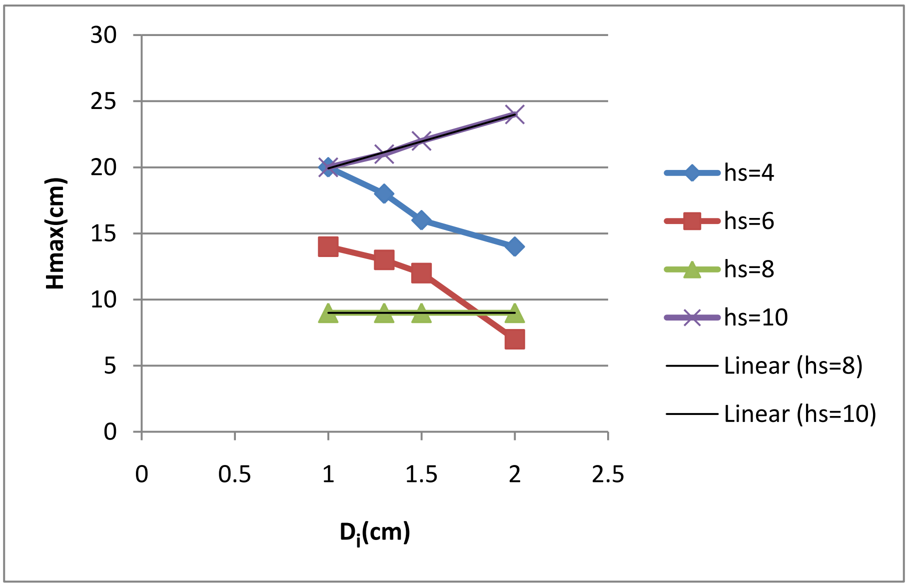


Fig. 5.5 Variation of fountain height with bed height for the 3.93mm glass bead.

At the present experiment the results show that the dolomite sample was the best material for spouting at fixed flow rate of 20 m^3/hr for the spouting.

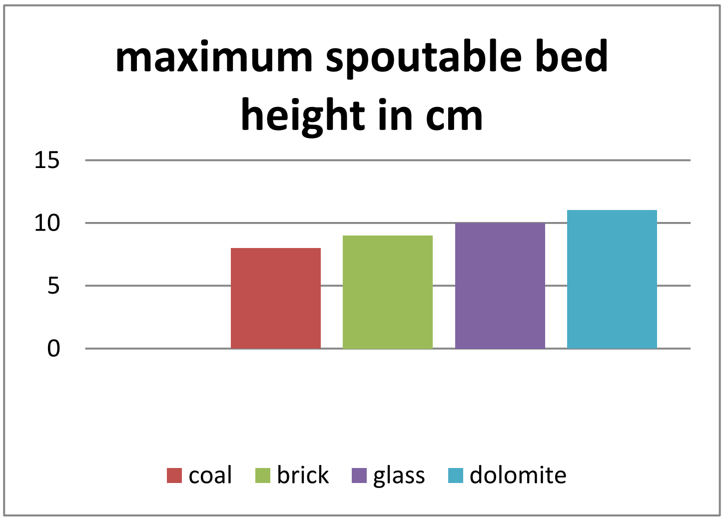


Fig. 5.6 Maximum spoutable bed height for the different bed materials

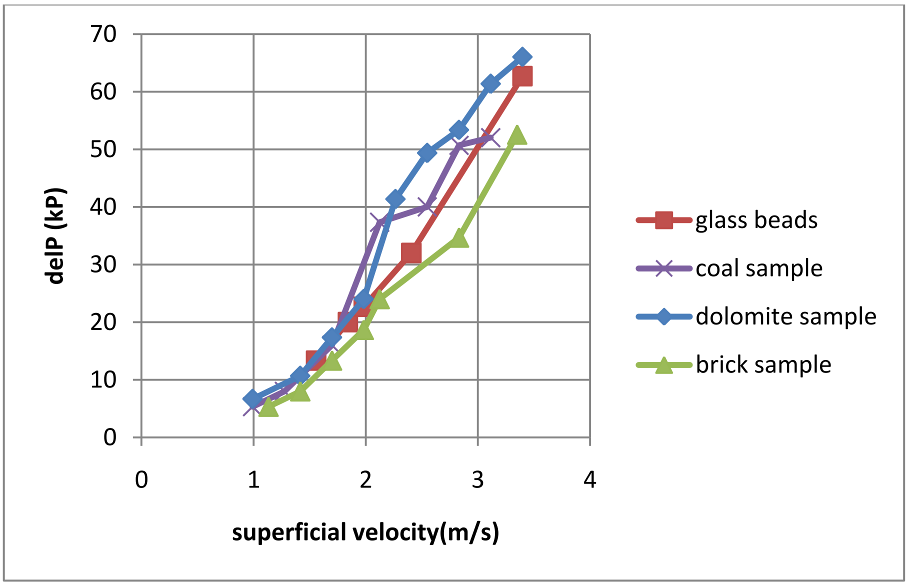


Fig. 5.7 pressure drop vs. superficial velocity at constant bed height, hs=6.

Table 5.5 Comparison of calculated values of fluidization index against the experimental values with the system parameters

DelU/U_0	H_s/D_c	d_i/d_c	ρ_s/ρ_f	d_p/D_c	product	F.I	FI. Cal.	Deviation (%)
0.2	1.6	0.2	2227	0.0786	1.149	1.1448	1.137	0.611
0.3	1.6	0.2	2227	0.0786	1.355	1.4828	1.348	9.058
0.4	1.6	0.2	2227	0.0786	1.523	1.6172	1.521	5.934
0.5	1.6	0.2	2227	0.0786	1.668	1.6508	1.670	-1.182
0.4	0.8	0.2	2227	0.0786	3.026	2.8223	3.088	-9.522
0.4	1.2	0.2	2227	0.0786	2.025	1.7522	2.040	-16.49
0.4	1.6	0.2	2227	0.0786	1.523	1.6183	1.521	5.980
0.4	2.0	0.2	2227	0.0786	1.221	1.0776	1.213	-12.38
0.4	1.6	0.2	2227	0.0786	1.523	1.6172	1.521	5.934
0.4	1.6	0.26	2227	0.0786	1.132	0.8073	1.119	-38.71
0.4	1.6	0.3	2227	0.0786	0.963	0.7933	0.947	-19.49
0.4	1.6	0.4	2227	0.0786	0.6954	0.7442	0.677	8.997
0.4	1.6	0.2	2805	0.0786	1.4022	1.7643	1.396	20.84
0.4	1.6	0.2	2227	0.0786	1.5237	1.8572	1.521	18.090
0.4	1.6	0.2	1845	0.0786	1.6305	2.0000	1.634	18.430
0.4	1.6	0.2	1601	0.0786	1.7159	2.1684	1.719	20.694
0.4	1.6	0.2	2227	0.0932	1.3134	1.0512	1.305	-24.186
0.4	1.6	0.2	2227	0.0786	1.5237	1.6184	1.521	5.980
0.4	1.6	0.2	2227	0.068	1.7283	1.6984	1.732	-2.009
0.4	1.6	0.2	2227	0.0528	2.1539	1.8184	2.174	-19.57

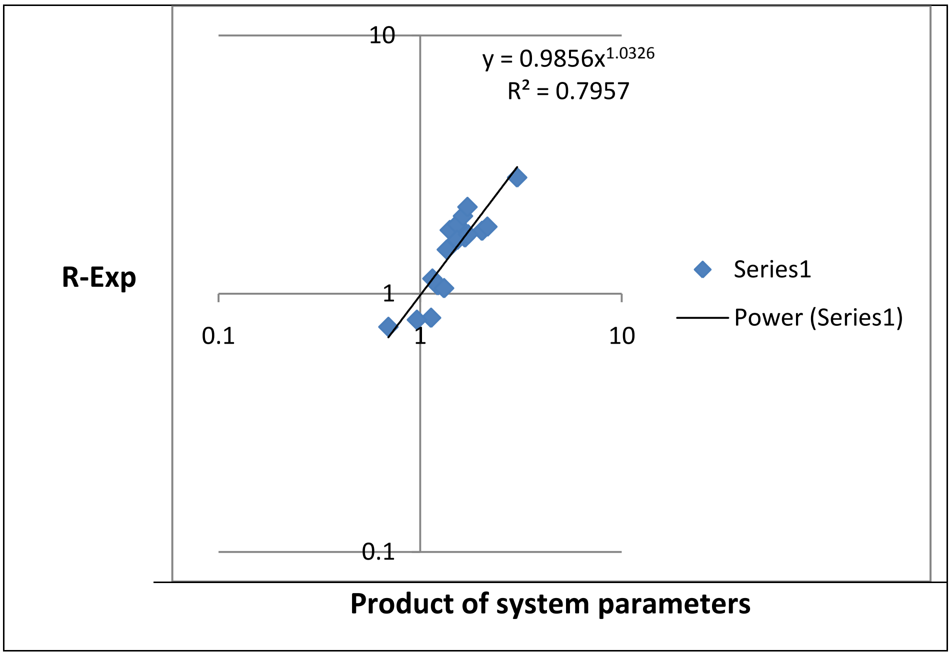


Figure 5.8 Correlation plot for the fluidization index against the system parameters

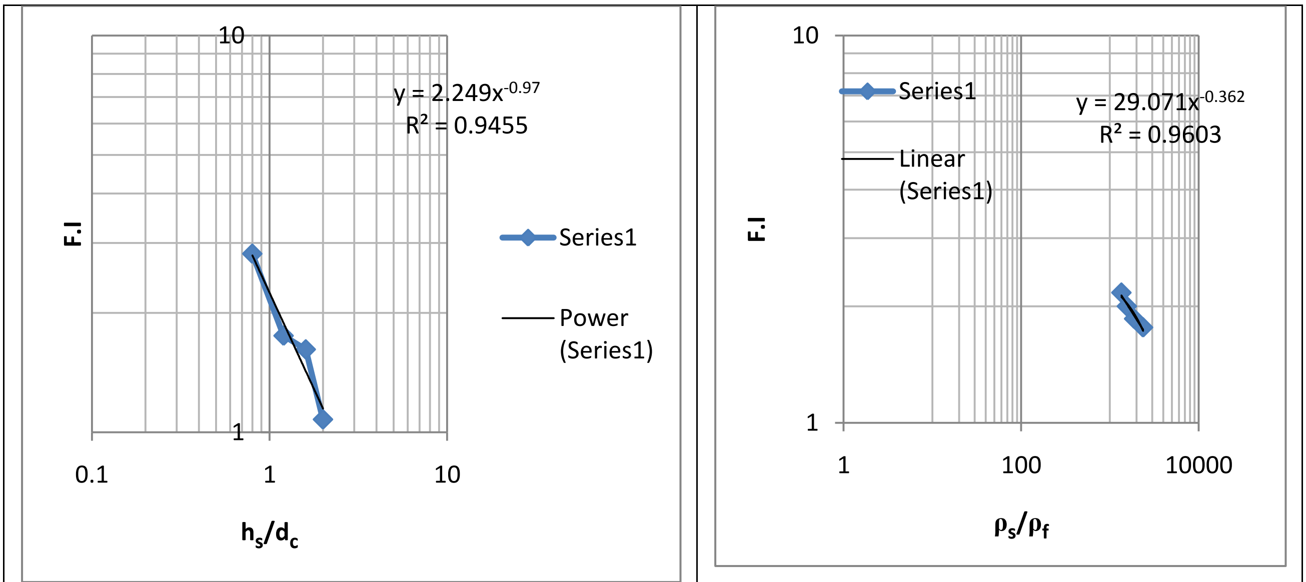
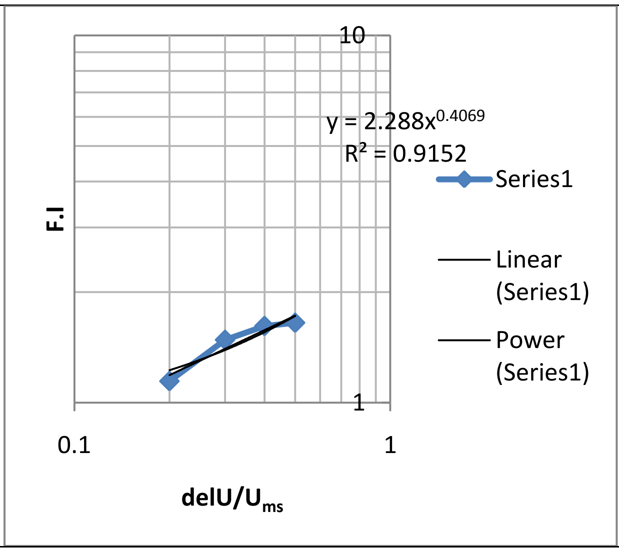


Fig. 5.9. (a) F.I vs. h_s/d_c and **(b). for the F.I VS density plot**



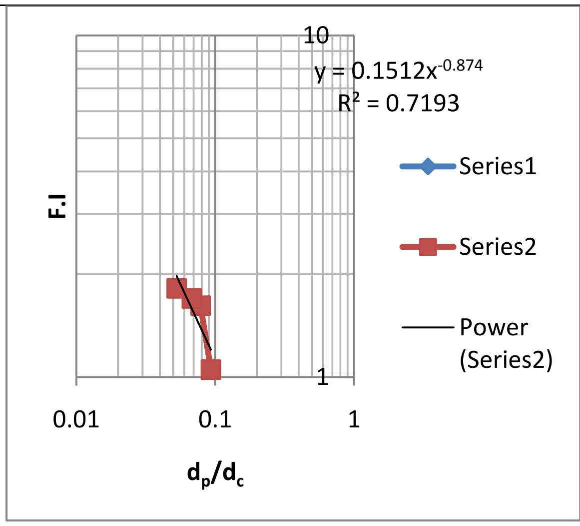


Fig. 5.10 (a) F.I vs delU/U_{ms}	(b)F.I vs. d_p/d_c plot

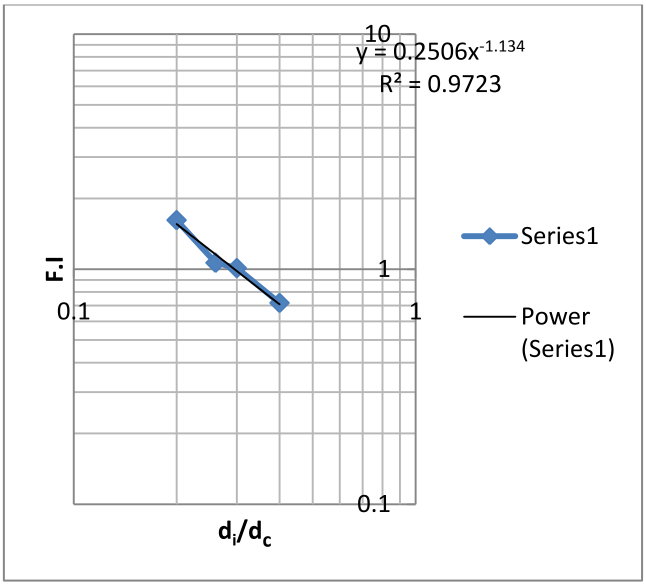


Fig. 5. 11 F.I vs. d_i/d_c plot

Figure 5.9 to 5.11 Variation of fluidization index with the individual system parameters

Table 5.6 Comparison of calculated values of bed expansion ratio against the experimental values with the system parameters

$\Delta(U)/U_{ms}$	H_s/D_c	d_i/d_c	ρ_s/ρ_f	d_p/D_c	product	R-exp	R-Cal	%dev
0.2	1.6	0.2	2227	0.0786	5.16E-09	1.21	1.183	2.199
0.3	1.6	0.2	2227	0.0786	5.91E-09	1.53	1.412	7.652
0.4	1.6	0.2	2227	0.0786	6.50E-09	1.59	1.602	-0.773
0.5	1.6	0.2	2227	0.0786	7.00E-09	1.65	1.766	-7.061
0.4	0.8	0.2	2227	0.0786	7.52E-09	1.65	1.939	-17.563
0.4	1.2	0.2	2227	0.0786	6.90E-09	1.54	1.733	-12.635
0.4	1.6	0.2	2227	0.0786	6.50E-09	1.46	1.602	-9.746
0.4	2.0	0.2	2227	0.0786	6.20E-09	1.34	1.506	-12.43
0.4	1.6	0.2	2227	0.0786	6.50E-09	1.46	1.602	-9.746
0.4	1.6	0.26	2227	0.0786	6.82E-09	1.50	1.708	-13.888
0.4	1.6	0.3	2227	0.0786	7.01E-09	1.59	1.769	-11.263
0.4	1.6	0.4	2227	0.0786	7.39E-09	1.65	1.897	-15.021
0.4	1.6	0.2	2805	0.0786	3.69E-09	1.46	0.762	47.757
0.4	1.6	0.2	2227	0.0786	6.50E-09	1.53	1.602	-4.725
0.4	1.6	0.2	1845	0.0786	1.03E-08	3.71	2.935	20.884
0.4	1.6	0.2	1601	0.0786	1.45E-08	7.45	4.632	37.819
0.4	1.6	0.2	2227	0.0932	6.18E-09	1.53	1.501	1.852
0.4	1.6	0.2	2227	0.0786	6.50E-09	1.59	1.602	0.773
0.4	1.6	0.2	2227	0.068	6.78E-09	1.65	1.693	2.6163
0.4	1.6	0.2	2227	0.0528	7.29E-09	1.21	1.864	-54.083

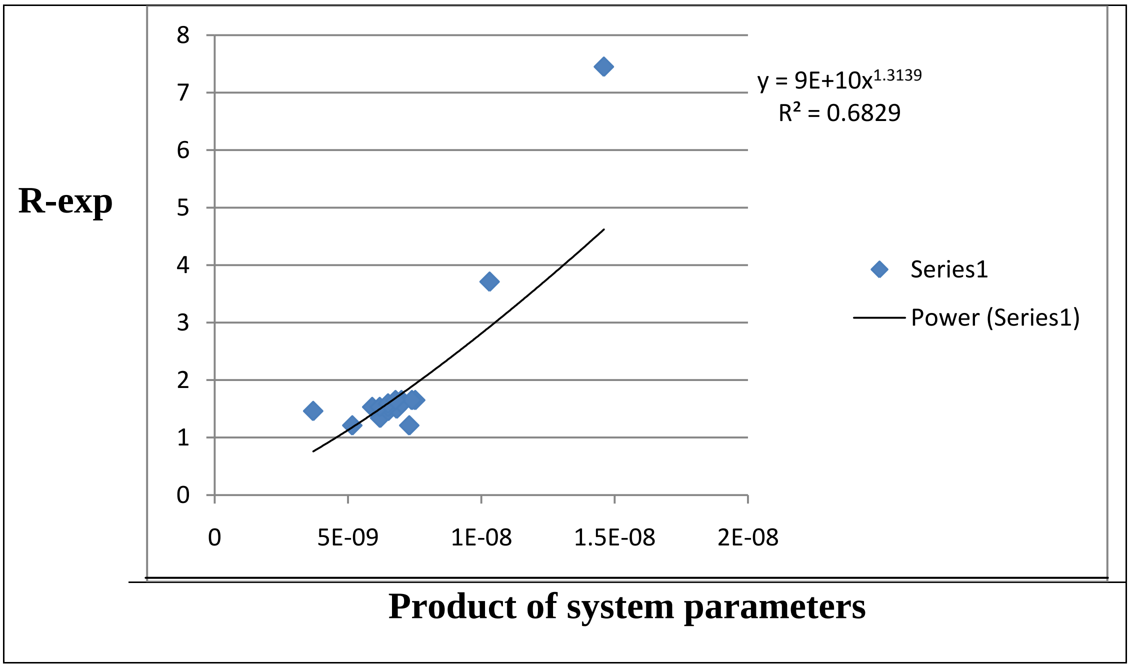
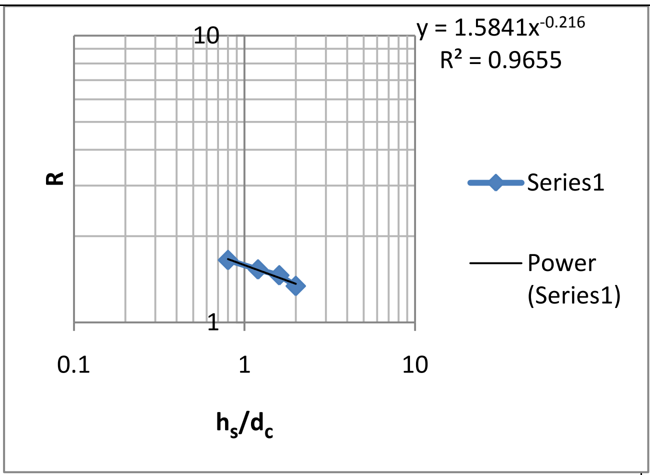


Figure 5.12 Correlation plot for the bed expansion ratio against the system parameters



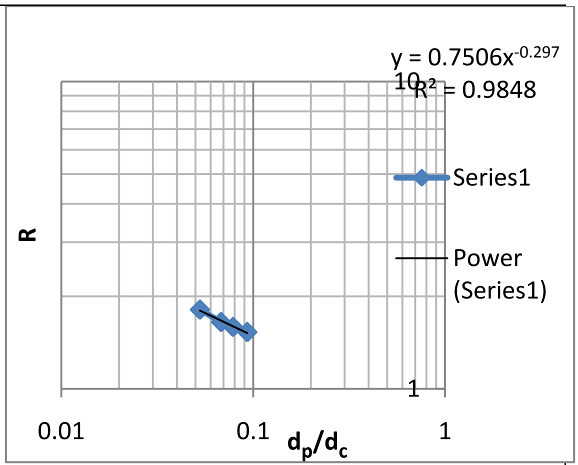
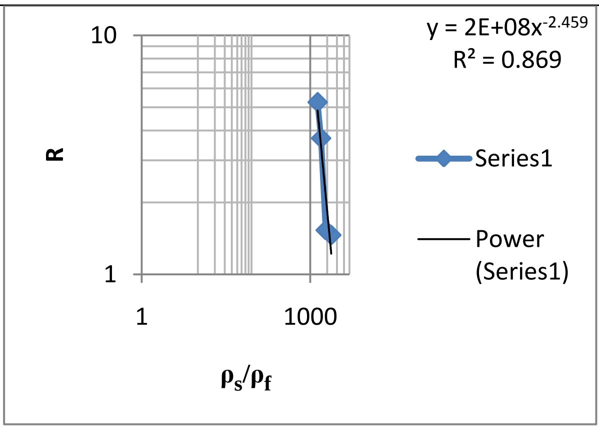


Fig. 5.13 (a)R vs. d_s/d_c	**(b)R vs d_p/d_c graphs**



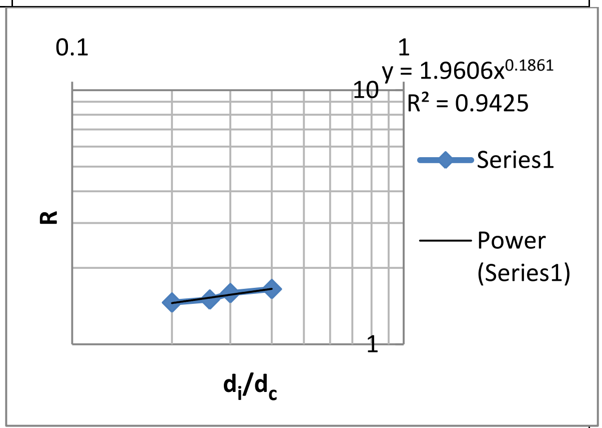


Fig. 5.14(a) R VS ρ_s/ρ_f .	**(b)R vs d_i/d_c**

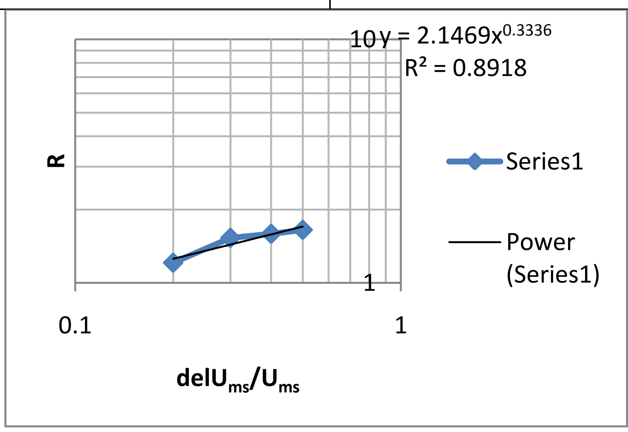


Fig. 5.15 R VS $delU/U_{ms}$

Figure 5.13 to 5.15 Variation of bed expansion ratio with the individual system parameters

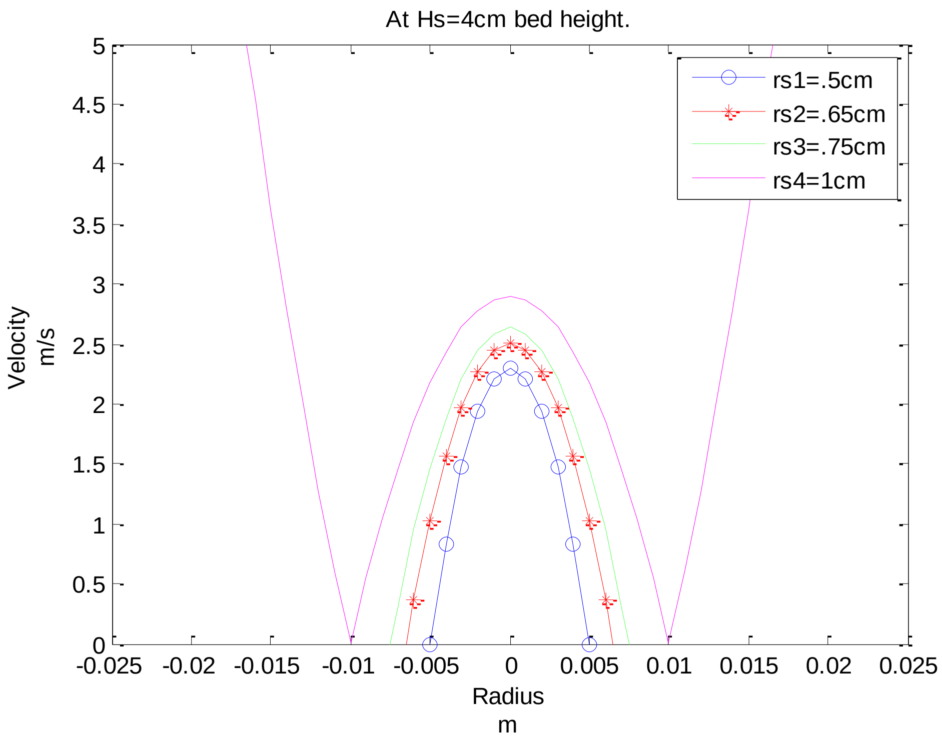


Fig. 5.16. Plot of Velocity profiles of bed materials (at H_s=4cm) in the axial direction for different spout diameters

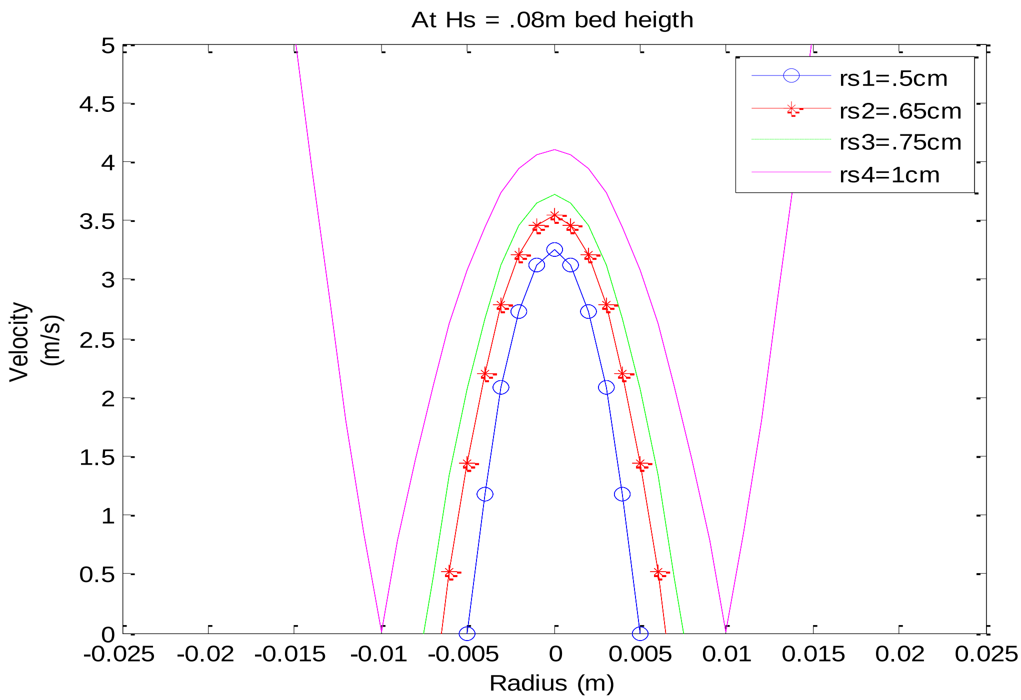


Fig. 5.17. Plot of Velocity profiles of bed materials (at H_s=8cm) in the axial direction for different spout diameters

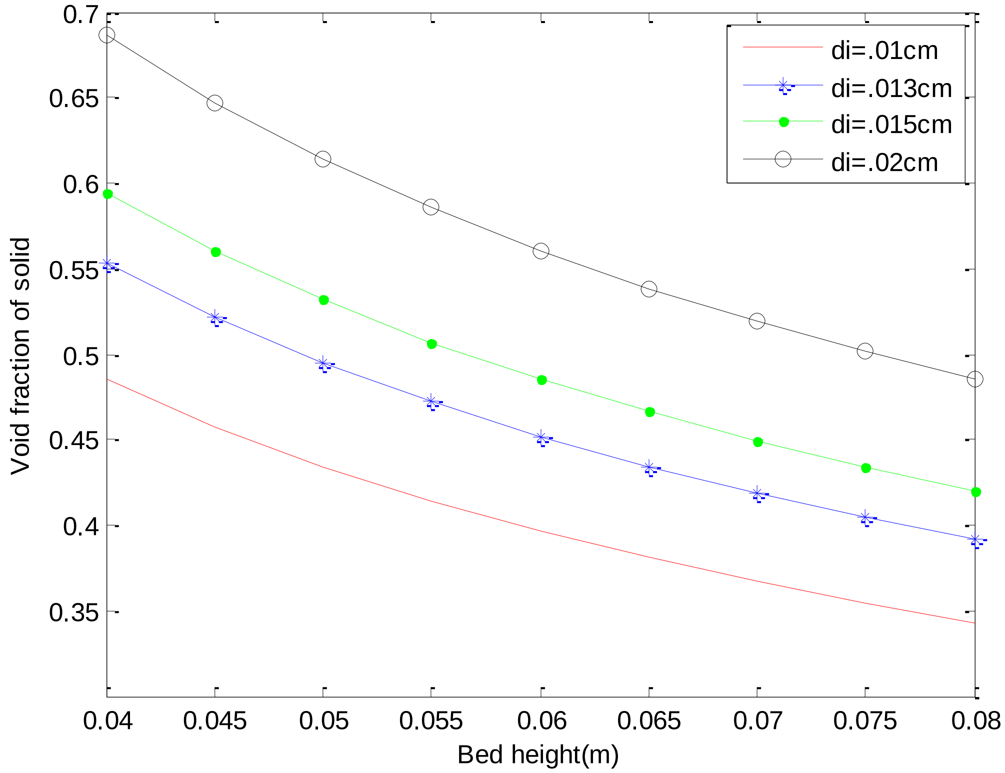


Fig. 5.18 Plot of Voidage profile against bed height for glass bead sample for different spout diameters.

Chapter 6

Conclusion

In the present work the attempt had been made to study the fluidization behavior of spouted bed. A minimum spoutable depth has however, not been previously defined or investigated. No detailed study had been made so far about maximum spouting velocity, at which transition from coherent spouting to either bubbling fluidization or slugging occurs. However for most practical purpose, there is usually ample latitude between the minimum and maximum spouting velocity so that velocity can be increased by a large factor without any transition to fluidization according to different system conditions such as spout size, particle size, shape of particle and density etc. Attempt has been made for detail analysis on the experimental data from which the following conclusions can be drawn.

1. Spouted bed is a phenomenon which is applicable for a wide range of particle density materials.
2. Pressure drop before beginning of the spouting is higher than the spouting pressure drop, than the spouting pressure drop decreases and becomes constant and on increasing flow rate it start behaving like fluidization.
3. By changing the parameters like material density, size of particles, orifice diameter, initial static bed height, one can conclude that these parameters affect the spouting behavior to a great extent.
4. Higher the spouting height better will be the operation and reaction will take place smoothly because of creation of more volume for contact. For the ranges of

parameters used in experiment, one can have clear idea about the spout height required for a better reactor design.

5. The calculated values of the fluidization index and the bed expansion ratio from developed correlations were found to match well with experimentally observed values indicating its application over a wide range of parameters. The developed correlations can therefore be used for studying the fluidization/spouting behavior in the industrial scale with proper scale up. The spouted behavior with different parameters gives the idea of energy conservation for various industries which are of great concern in the present scenario.

6. By the mathematical modeling of the spouting bed one can analyze the behaviour of the bed/reactor by changing parameters within a few seconds of time thereby avoiding time-taking long procedure of experiment.

The discretization of the governing equation in turn numerical expression will be of great importance for the study of spouted bed reactors in reality.

6.1 Future Work

Spouted bed has lot of industrial uses. The efficiency of spouted bed can further be improved by many modifications or changes in the system variables.

- Utilization of multiple spouts in a single column, may be used as separating technique of particulate,
- Development of the CFD and DEM models for spouted bed is the important for the fine particles such as in Nano and microns size of particles as the use of spouted column as a reactor is important in comparison with other types because the fine particles are not suitable for the spouting.

Nomenclature

R= expansion ration

F.I=fluidization index

K=numerical co-efficient for expansion ratio

K'=numerical co-efficent for fluidization index

H_s=static bed height

d_c= column diameter

d_p= partical diameter

d_i=spout diameter(orifice diameter)

U_o= superficial velocity

U_{ms}= minimum fludization velocity

ρ_s = density of solid particles

ρ_f = density of fluid

a,*b*,*c*,*d*,*e* and *n* are exponents for expansion ratio*(R)* correlation

a', b', c',d', e' and *n*' are exponents for *F.I* ratio correlation

ε_g ε_s void fraction of gas and solid.

v_{rg} v_{zg} $v_{\theta g}$ are the velocity component of gas in r, z and angular

ρ_s ρ_f solid and gas density respectively

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Appendix

Table2. For brick beads (d=0.00393m) d_i=1cm

h_s=4cm

Q m^3/hr	L1 m	L2 m	Hsp m.	Hmin m	Hmax m	ρ (kg/m^3)	A (m^2)	G m/s^2	Δh m	V=q/A m/s	ΔP (kP)
6	0.515	0.485	0.1	-	-	13600	0.0019662	9.81	0.03	0.8476	4.0024
7	0.52	0.48	0.15	-	-	13600	0.0019662	9.81	0.04	0.9889	5.3366
8	0.52	0.48	0.16	-	-	13600	0.0019662	9.81	0.04	1.1302	5.3366
10	0.53	0.47	0.23	-	-	13600	0.0019662	9.81	0.06	1.4127	8.0049
12	0.545	0.455	0.3	-	-	13600	0.0019662	9.81	0.09	1.6953	12.007
14	0.58	0.42	0.32	-	-	13600	0.0019662	9.81	0.16	1.9772	21.346
16	0.58	0.42	0.34	-	-	13600	0.0019662	9.81	0.16	2.2604	21.346
20	0.65	0.35	0.42	-	-	13600	0.0019662	9.81	0.3	2.8255	40.024
24	0.65	0.35	0.44	-	-	13600	0.0019662	9.81	0.3	3.3906	40.024

H_s=6cm

8	0.52	0.48	0.1	-	-	13600	0.001962	9.81	0.04	1.132631	5.33664
10	0.53	0.47	0.14	-	-	13600	0.001962	9.81	0.06	1.415789	8.00496
12	0.55	0.45	0.19	-	-	13600	0.001962	9.81	0.1	1.698947	13.3416
14	0.57	0.43	0.24	-	-	13600	0.001962	9.81	0.14	1.982104	18.6782
15	0.59	0.41	0.3	-	-	13600	0.001962	9.81	0.18	2.123683	24.0148
20	0.63	0.37	0.45	-	-	13600	0.001962	9.81	0.26	2.831578	34.6881

Hs=8 cm

9	0.535	0.465	0.11			13600	0.001962	9.81	0.07	1.27421	9.33912
12	0.56	0.44	0.19			13600	0.001962	9.81	0.12	1.698947	16.00992
15	0.61	0.39	0.25			13600	0.001962	9.81	0.22	2.123683	29.35152
20	0.67	0.33	0.5			13600	0.001962	9.81	0.34	2.831578	45.36144
24	0.73	0.27	0.55			13600	0.001962	9.81	0.46	3.397893	61.37136

Hs=10cm

9	0.535	0.465	12			13600	0.001962	9.81	0.07	1.27421	9.33912
12	0.54	0.46	14			13600	0.001962	9.81	0.08	1.698947	10.67328
15	0.58	0.42		13	16	13600	0.001962	9.81	0.16	2.123683	21.34656
17	0.62	0.38		15	17	13600	0.001962	9.81	0.24	2.406841	32.01984
20	0.66	0.34		19	22	13600	0.001962	9.81	0.32	2.831578	42.69312
22	0.67	0.33		21	24	13600	0.001962	9.81	0.34	3.114736	45.36144
23	0.7	0.3	44			13600	0.001962	9.81	0.4	3.256314	53.3664

H_s=12cm

9	0.535	0.465	13			13600	0.001962	9.81	0.07	1.274	9.33912
11	0.55	0.45		14	17	13600	0.001962	9.81	0.1	1.557	13.3416
14	0.58	0.42		17	19	13600	0.001962	9.81	0.16	1.982	21.34656
17	0.62	0.38		21	23	13600	0.001962	9.81	0.24	2.406	32.01984
20	0.69	0.31	33			13600	0.001962	9.81	0.38	2.831	50.69808
22	0.69	0.31	34			13600	0.001962	9.81	0.38	3.114	50.69808

Table for coal bead (d_p=.00393m) d_i=1cm

H_s=3cm

Q m^3/hr	l1 m	l2 m	Hsp m.	Hmin m	Hmax m	ρ (kg/m^3)	A (m^2)	G m/s^2	Δh m	V=q/A m/s	ΔP (kP)
6	0.51	0.49	0.04			13600	0.001962	9.81	0.02	0.849473	2.66832
8	0.515	0.485	0.08			13600	0.001962	9.81	0.03	1.132631	4.00248
9	0.5	0.5	0.25			13600	0.001962	9.81	0	1.27421	0
10	0.54	0.46	0.28			13600	0.001962	9.81	0.08	1.415789	10.67328
12	0.62	0.38		0.28	0.29	13600	0.001962	9.81	0.24	1.698947	32.01984
18	0.68	0.32		0.3	0.44	13600	0.001962	9.81	0.36	2.54842	48.02976

Hs=4cm

6	0.515	0.485	0.1			13600	0.001962	9.81	0.03	0.849473	
7	0.52	0.48	0.12			13600	0.001962	9.81	0.04	0.991052	5.33664
9	0.53	0.47	0.26			13600	0.001962	9.81	0.06	1.27421	8.00496
12	0.56	0.44	0.32			13600	0.001962	9.81	0.12	1.698947	16.00992
15	0.64	0.36		0.35	0.38	13600	0.001962	9.81	0.28	2.123683	37.35648
18	0.65	0.35		0.44	0.48	13600	0.001962	9.81	0.3	2.54842	40.0248
20	0.69	0.31		0.48	0.52	13600	0.001962	9.81	0.38	2.831578	50.69808
22	0.71	0.29		0.41	0.55	13600	0.001962	9.81	0.42	3.114736	56.03472

Hs=6cm

6	0.515	0.485	8			13600	0.001962	9.81	0.03	0.849	4.00248
8	0.525	0.475	16			13600	0.001962	9.81	0.05	1.132	6.6708
9	0.53	0.47		16	18	13600	0.001962	9.81	0.06	1.273	8.00496
11	0.555	0.445		21	24	13600	0.001962	9.81	0.11	1.557	14.67576
12	0.56	0.44		26	27	13600	0.001962	9.81	0.12	1.698	16.00992
14	0.58	0.42		32	35	13600	0.001962	9.81	0.16	1.982	21.34656
15	0.6	0.4		40	42	13600	0.001962	9.81	0.2	2.123	26.6832
16	0.625	0.375		45	47	13600	0.001962	9.81	0.25	2.265	33.354
18	0.67	0.33		53	55	13600	0.001962	9.81	0.34	2.548	45.36144

Hs=8cm

7	0.53	0.47	11			13600	0.001962	9.81	0.06	0.9910	8.00496
8	0.535	0.465	14			13600	0.001962	9.81	0.07	1.1326	9.33912
10	0.54	0.46		14	16	13600	0.001962	9.81	0.08	1.4157	10.67328
11	0.55	0.45		16	17	13600	0.001962	9.81	0.1	1.5573	13.3416
12	0.57	0.43		21	22	13600	0.001962	9.81	0.14	1.6989	18.67824
14	0.6	0.4		54	55	13600	0.001962	9.81	0.2	1.9821	26.6832
18	0.65	0.35		54	57	13600	0.001962	9.81	0.3	2.548	40.0248
20	0.7	0.3		55	60	13600	0.001962	9.81	0.4	2.8319	53.3664

Hs=10cm

8	0.525	0.475	15			13600	0.001962	9.81	0.05	1.1326	6.6708
9	0.54	0.46	18			13600	0.001962	9.81	0.08	1.2749	10.673
11	0.55	0.45		17	19	13600	0.001962	9.81	0.1	1.5573	13.341
12	0.56	0.44		19	21	13600	0.001962	9.81	0.12	1.6989	16.009
15	0.59	0.41		21	23	13600	0.001962	9.81	0.18	2.1236	24.014
17	0.64	0.36		48	52	13600	0.001962	9.81	0.28	2.4068	37.356
19	0.68	0.32		75	80	13600	0.001962	9.81	0.36	2.6899	48.029

Hs=12cm

8	0.53	0.47		14	15	13600	0.001962	9.81	0.06	1.1326	8.00496
9	0.535	0.465		15	20	13600	0.001962	9.81	0.07	1.2747	9.33912
11	0.55	0.45		16	21	13600	0.001962	9.81	0.1	1.5573	13.3416
13	0.58	0.42		26	28	13600	0.001962	9.81	0.16	1.8405	21.3469
15	0.6	0.4		25	29	13600	0.001962	9.81	0.2	2.1236	26.6832
18	0.65	0.35		25	45	13600	0.001962	9.81	0.3	2.5484	40.0248
20	0.7	0.3		75	78	13600	0.001962	9.81	0.4	2.8315	53.3664

Hs=14cm

8	0.53	0.47		16	18	13600	0.001962	9.81	0.06	1.132631	8.00496
9	0.535	0.465		18	29	13600	0.001962	9.81	0.07	1.27421	9.33912
11	0.54	0.46		19	29	13600	0.001962	9.81	0.08	1.557368	10.67328
12	0.58	0.42		21	30	13600	0.001962	9.81	0.16	1.698947	21.34656
14	0.59	0.41		24	32	13600	0.001962	9.81	0.18	1.982104	24.01488
17	0.65	0.35		32	42	13600	0.001962	9.81	0.3	2.406841	40.0248
20	0.71	0.29		65	67	13600	0.001962	9.81	0.42	2.831578	56.03472
22	0.76	0.24		85	88	13600	0.001962	9.81	0.52	3.114736	69.37632

Tables for the dolomite (.00393m) d_i=1cm

Hs=3cm

Q m^3/hr	l1 m	l2 m	Hsp m.	Hmin m	Hmax m	ρ (kg/m^3)	A (m^2)	G m/s^2	Δh m	V=q/A m/s	ΔP (kP)
9	0.515	0.485	10			13600	0.001962	9.81	0.03	1.274	4.00248
10	0.545	0.455	21			13600	0.001962	9.81	0.09	1.415	12.00744
13.5	0.58	0.42	29			13600	0.001962	9.81	0.16	1.911	21.34656
15.5	0.645	0.355	30			13600	0.001962	9.81	0.29	2.194	38.69064
18	0.665	0.335	31			13600	0.001962	9.81	0.33	2.548	44.02728
20	0.68	0.32	32			13600	0.001962	9.81	0.36	2.831	48.02976
22	0.71	0.29	33			13600	0.001962	9.81	0.42	3.114	56.03472
24	0.75	0.25	37			13600	0.001962	9.81	0.5	3.397	66.708

Hs=4cm

7	0.525	0.475	0.9			13600	0.001962	9.81	0.05	0.991	6.6708
10	0.54	0.46	0.14			13600	0.001962	9.81	0.08	1.415	10.67328
12	0.565	0.435	0.16			13600	0.001962	9.81	0.13	1.698	17.34408
14	0.59	0.41	0.22			13600	0.001962	9.81	0.18	1.982	24.01488
16	0.655	0.345	0.27			13600	0.001962	9.81	0.31	2.265	41.35896
18	0.685	0.315	0.28			13600	0.001962	9.81	0.37	2.548	49.36392
20	0.7	0.3	0.32			13600	0.001962	9.81	0.4	2.831	53.3664
22	0.73	0.27	0.36			13600	0.001962	9.81	0.46	3.114	61.37136
24	0.74	0.26	0.39			13600	0.001962	9.81	0.48	3.397	64.03968

Hs=6cm

11	0.555	0.445	7			13600	0.001962	9.81	0.11	1.557	14.675
11.5	0.565	0.435	11			13600	0.001962	9.81	0.13	1.628	17.342
13	0.58	0.42	14			13600	0.001962	9.81	0.16	1.840	21.346
15	0.62	0.38	16			13600	0.001962	9.81	0.24	2.123	32.019
15.5	0.625	0.375		12	15	13600	0.001962	9.81	0.25	2.194	33.354
17	0.64	0.36		18	20	13600	0.001962	9.81	0.28	2.406	37.356
19	0.68	0.32		27	29	13600	0.001962	9.81	0.36	2.68	48.029
22	0.725	0.275		30	34	13600	0.001962	9.81	0.45	3.11	60.032
24	0.78	0.22		42	44	13600	0.001962	9.81	0.56	3.397	74.712

Hs=8cm

12	0.57	0.43	9			13600	0.001962	9.81	0.14	1.69894	18.6782
14	0.595	0.405	14			13600	0.001962	9.81	0.19	1.98210	25.3490
15	0.61	0.39	16			13600	0.001962	9.81	0.22	2.12368	29.3515
18	0.675	0.325		15	17	13600	0.001962	9.81	0.35	2.54841	46.6956
20	0.7	0.3		17	18	13600	0.001962	9.81	0.4	2.83157	53.3664
22	0.71	0.29		25	28	13600	0.001962	9.81	0.42	3.11473	56.0347
24	0.745	0.255		31	33	13600	0.001962	9.81	0.49	3.39789	65.3738

Hs=10cm

11.5	0.57	0.43		14	16	13600	0.001962	9.81	0.14	1.62815	18.678
14	0.605	0.395		15	16	13600	0.001962	9.81	0.21	1.98210	28.017
16	0.655	0.345		19	21	13600	0.001962	9.81	0.31	2.26526	41.352
19	0.705	0.295		21	25	13600	0.001962	9.81	0.41	2.68999	54.700
22	0.75	0.25		22	26	13600	0.001962	9.81	0.5	3.11473	66.708
24	0.76	0.24				13600	0.001962	9.81	0.52	3.39789	69.376

Hs=12cm

11	0.56	0.44	16			13600	0.001962	9.81	0.12	1.55736	16.009
14	0.59	0.41		16	22	13600	0.001962	9.81	0.18	1.98210	24.014
16	0.63	0.37		17	23	13600	0.001962	9.81	0.26	2.26526	34.688
19	0.67	0.33		21	27	13600	0.001962	9.81	0.34	2.68999	45.361
22	0.73	0.27		24	30	13600	0.001962	9.81	0.46	3.11473	61.371
24	0.75	0.25		24	30	13600	0.001962	9.81	0.5	3.39789	66.708

Hs=14cm

11.5	0.56	0.44	16			13600	0.001962	9.81	0.12	1.62815	16.009
13	0.58	0.42		17	25	13600	0.001962	9.81	0.16	1.84052	21.346
15	0.625	0.375		22	33	13600	0.001962	9.81	0.25	2.12368	33.354
18	0.66	0.34		24	44	13600	0.001962	9.81	0.32	2.54841	42.693
20	0.67	0.33		26	56	13600	0.001962	9.81	0.34	2.83157	45.361
24	0.74	0.26		30	62	13600	0.001962	9.81	0.48	3.39789	64.039

Hs=16cm

11	0.56	0.44	18			13600	0.001962	9.81	0.12	1.5573	16.009
12.5	0.58	0.42		0.21	0.24	13600	0.001962	9.81	0.16	1.7697	21.346
16.5	0.62	0.38		0.21	0.36	13600	0.001962	9.81	0.24	2.3360	32.019
19	0.68	0.32		0.24	0.46	13600	0.001962	9.81	0.36	2.6899	48.029

Glass bead (.0046m) for di=1cm

Hs=4cm

Q m^3/hr	l1 m	l2 m	Hsp m.	Hmin m	Hmax m	ρ (kg/m^3)	A (m^2)	G m/s^2	Δh m	V=q/A m/s	ΔP (kP)
9	52.5	47.5	5			13600	0.001962	9.81	5	1.2742	6.6708
12	54.5	45.5	12			13600	0.001962	9.81	9	1.6989	12.007
17	61	39	19			13600	0.001962	9.81	22	2.4068	29.351
20	65	35	21			13600	0.001962	9.81	30	2.8315	40.022
24	71	29	22			13600	0.001962	9.81	42	3.3978	56.034
26	72	28	24			13600	0.001962	9.81	44	3.68105	58.703

Hs=6cm

11	53.5	46.5	7			13600	0.001962	9.81	7	1.5573	9.33912
13	55	45	10			13600	0.001962	9.81	10	1.8405	13.3416
16	59	41	12			13600	0.001962	9.81	18	2.2652	24.01488
20	66	34	19			13600	0.001962	9.81	32	2.8315	42.69312
24	72	28	22			13600	0.001962	9.81	44	3.3978	58.70304
26	75	25	24			13600	0.001962	9.81	50	3.6810	66.708

Hs=8cm

13	54.5	45.5	9			13600	0.001962	9.81	9	1.84052	12.00744
17.5	59	41	12			13600	0.001962	9.81	18	2.47762	24.01488
20	62.8	37.2	15			13600	0.001962	9.81	25.6	2.83157	34.154496
26	73	27	21			13600	0.001962	9.81	46	3.68102	61.37136

Hs=10cm

12	54.5	45.5	11			13600	0.001962	9.81	9	1.69894	12.007
16.5	57.5	42.5		11	16	13600	0.001962	9.81	15	2.33605	20.012
20	63	37		14	15	13600	0.001962	9.81	26	2.83157	34.688
24	68.5	31.5		17		13600	0.001962	9.81	37	3.39789	49.363
26	72.5	27.5		19		13600	0.001962	9.81	45	3.68105	60.037

Hs=12cm

12	54.5	45.5		13	14	13600	0.001962	9.81	9	1.6989	12.00
14	57	43		14	20	13600	0.001962	9.81	14	1.9821	18.678
18	60	40		14	22	13600	0.001962	9.81	20	2.5484	26.682
20	63	37		16	31	13600	0.001962	9.81	26	2.8315	34.688
24	67.5	32.5		18	21	13600	0.001962	9.81	35	3.3978	46.692
26	70	30		21	23	13600	0.001962	9.81	40	3.6810	53.366

Glass bead (.00393m) and di=1cm

Hs=4cm

Q m^3/hr	l1 m	l2 m	Hsp m.	Hmin m	Hmax m	ρ (kg/m^3)	A (m^2)	G m/s^2	Δh m	V=q/A m/s	ΔP (kP)
9	53	47	6			13600	0.001962	9.81	6	1.2742	8.004
11	53.5	46.5	9			13600	0.001962	9.81	7	1.5573	9.339
12	54.4	45.6	10			13600	0.001962	9.81	8.8	1.6989	11.740
15	62.5	37.5	14			13600	0.001962	9.81	25	2.1236	33.322
19	65.6	34.4	16			13600	0.001962	9.81	31.2	2.6899	41.625
20	65.7	34.3	17			13600	0.001962	9.81	31.4	2.8315	41.892
24	71	29		7	20	13600	0.001962	9.81	42	3.3978	56.034
26	75	25		8	21	13600	0.001962	9.81	50	3.6810	66.708

Hs=5cm

11	55	45	7			13600	0.001962	9.81	10	1.5573	13.341
13	57.5	42.5	9			13600	0.001962	9.81	15	1.8405	20.012
14	58.5	41.5	10.5			13600	0.001962	9.81	17	1.9821	22.680
17	62	38	14			13600	0.001962	9.81	24	2.4068	32.019
24	75	25		7	19	13600	0.001962	9.81	50	3.3978	66.708

Hs=6cm

12	54.5	45.5	8			13600	0.001962	9.81	9	1.6989	12.007
14	55.5	44.5	10			13600	0.001962	9.81	11	1.9821	14.672
16	62.5	37.5	12			13600	0.001962	9.81	25	2.2652	33.352
20	65.5	34.5	14			13600	0.001962	9.81	31	2.8315	41.358
22	69	31	16			13600	0.001962	9.81	38	3.1147	50.698
24	72	28	18			13600	0.001962	9.81	44	3.3978	58.703
25	73	27	19			13600	0.001962	9.81	46	3.5394	61.371

Hs=8cm

12	54.5	45.5	9			13600	0.001962	9.81	9	1.69894	12.007
13	57.5	42.5		9	11	13600	0.001962	9.81	15	1.84052	20.012
15	59	41		10	12	13600	0.001962	9.81	18	2.12368	24.014
18	66	34	13			13600	0.001962	9.81	32	2.54841	42.693
20	69	31	14			13600	0.001962	9.81	38	2.83157	50.698
23	70	30	16			13600	0.001962	9.81	40	3.25631	53.362
25	73	27	17			13600	0.001962	9.81	46	3.53947	61.372

Hs=10cm

12	55.5	44.5	11			13600	0.001962	9.81	11	1.6989	14.675
13	58	42		11	14	13600	0.001962	9.81	16	1.8405	21.346
15	60	40		11	16	13600	0.001962	9.81	20	2.1236	26.682
16	62	38		12	18	13600	0.001962	9.81	24	2.2652	32.019
19	65	35		12	20	13600	0.001962	9.81	30	2.6899	40.024
22	71	29	16			13600	0.001962	9.81	42	3.11473	56.0347
24	71	29	20			13600	0.001962	9.81	42	3.39789	56.0347

Hs=12cm

12	55	45	12			13600	0.001962	9.81	10	1.6989	13.341
14	59	41		12	16	13600	0.001962	9.81	18	1.9822	24.014
16	52	48		12	18	13600	0.001962	9.81	4	2.2652	5.336
18	66	34		13	22	13600	0.001962	9.81	32	2.5484	42.69
22	72	28		9	19	13600	0.001962	9.81	44	3.1147	58.703

Glass bead (.0034m)for di=1cm

Hs=4cm

Q m^3/hr	l1 m	l2 m	Hsp m.	Hmin m	Hmax m	ρ (kg/m^3)	A (m^2)	G m/s^2	Δh m	V=q/A m/s	ΔP (kP)
6	51.5	48.5	5			13600	0.001962	9.81	3	0.84947	4.00248
8	53	47	9			13600	0.001962	9.81	6	1.1326	8.00496
10.5	55	45	15			13600	0.001962	9.81	10	1.4862	13.3416
14	61	39	16			13600	0.001962	9.81	22	1.98243	29.35152
16.5	65	35	17			13600	0.001962	9.81	30	2.33165	40.0248
20	71.5	28.5	21			13600	0.001962	9.81	43	2.83176	57.36888
22	75.5	24.5	22			13600	0.001962	9.81	51	3.11553	68.04216
24	77	23	23			13600	0.001962	9.81	54	3.39731	72.04464

Hs=6cm

9	55	45	7			13600	0.001962	9.81	10	1.63092	13.341
12	57.5	42.5	10			13600	0.001962	9.81	15	1.69894	20.012
14	59	41	12			13600	0.001962	9.81	18	1.98210	24.014
15	62	38	14			13600	0.001962	9.81	24	2.12362	32.019
17	66	34	16			13600	0.001962	9.81	32	2.40684	42.692
19	68	32	17			13600	0.001962	9.81	36	2.68999	48.029
22	71	29	19			13600	0.001962	9.81	42	3.11473	56.034

Hs=8cm

9	55	45	9			13600	0.001962	9.81	10	1.2742	13.341
12	57.5	42.5		9	11	13600	0.001962	9.81	15	1.6989	20.012
13	59	41	12			13600	0.001962	9.81	18	1.8405	24.014
15	62	38	14			13600	0.001962	9.81	24	2.1236	32.019
17	66	34	17			13600	0.001962	9.81	32	2.4068	42.693
19	68	32	19			13600	0.001962	9.81	36	2.6899	48.029
22	71	29	20			13600	0.001962	9.81	42	3.1147	56.034

Hs=9cm

11	54.5	45.5	10			13600	0.001962	9.81	9	1.5573	12.007
12	57	43		10	12	13600	0.001962	9.81	14	1.6989	18.678
16	59.5	40.5		11	14	13600	0.001962	9.81	19	2.2652	25.349
19	63.5	36.5		12	16	13600	0.001962	9.81	27	2.6899	36.022
20	68	32	15			13600	0.001962	9.81	36	2.8315	48.029
21	71	29	17			13600	0.001962	9.81	42	2.9731	56.032
24	74	26	18			13600	0.001962	9.81	48	3.3978	64.039
11	54.5	45.5	10			13600	0.001962	9.81	9	1.5573	12.007
12	57	43		10	12	13600	0.001962	9.81	14	1.6989	18.678

Hs=10cm

11	55.5	44.5		12	13	13600	0.001962	9.81	11	1.5573	14.672
14	59	41		13	17	13600	0.001962	9.81	18	1.9821	24.014
16	62.5	37.5		16	18	13600	0.001962	9.81	25	2.2652	33.322
20	71	29		17	20	13600	0.001962	9.81	42	2.8315	56.034
22	73	27		17	21	13600	0.001962	9.81	46	3.1147	61.371
24	76.5	23.5		17	22	13600	0.001962	9.81	53	3.3978	70.712

Hs=11cm

11.5	58.5	41.5		15	16	13600	0.001962	9.81	17	1.6281	22.680
14.5	60	40		15	20	13600	0.001962	9.81	20	2.0528	26.683
18	67.5	32.5		15	22	13600	0.001962	9.81	35	2.54841	46.692
20	71	29		17	23	13600	0.001962	9.81	42	2.8315	56.034
22	73.5	26.5		17	25	13600	0.001962	9.81	47	3.1147	62.705
24	74	26		20	27	13600	0.001962	9.81	48	3.3978	64.039

Hs=12cm

11.5	56	44		12	13	13600	0.001962	9.81	12	1.6282	16.002
13	58	42		13	17	13600	0.001962	9.81	16	1.8405	21.342
14	60	40		15	21	13600	0.001962	9.81	20	1.9821	26.683
18	66	34		15	26	13600	0.001962	9.81	32	2.5484	42.693
20	67	33		18	29	13600	0.001962	9.81	34	2.8315	45.361
22	71	29		19	31	13600	0.001962	9.81	42	3.1147	56.034
24	74	26		21	32	13600	0.001962	9.81	48	3.3978	64.039

Hs=14cm

11.5	58	42		16	17	13600	0.001962	9.81	16	1.6281	21.346
12	58	42		18	20	13600	0.001962	9.81	16	1.6989	21.346
16.5	62	38		22	43	13600	0.001962	9.81	24	2.3360	32.019
19	70	30		29	50	13600	0.001962	9.81	40	2.6899	53.362

Glass bead (.00264m) for di=1cm

Hs=3cm

Q m^3/hr	l1 m	l2 m	Hsp m	Hmin m	Hmax m	ρ (kg/m^3)	A (m^2)	G m/s^2	Δh m	V=q/A m/s	ΔP (kP)
7	52	48	6			13600	0.001962	9.81	4	0.991	5.336
9	53	47	10			13600	0.001962	9.81	6	1.274	8.002
12	54	46	14			13600	0.001962	9.81	8	1.696	10.672
16	58	42	20			13600	0.001962	9.81	16	2.265	21.346
18	60	40	21			13600	0.001962	9.81	20	2.548	26.682
23	64	36	26			13600	0.001962	9.81	28	3.256	37.356
24	65	35	28			13600	0.001962	9.81	30	3.393	40.022
27	66	34	29			13600	0.001962	9.81	32	3.822	42.693

Hs=4cm

Q m^3/hr	l1 m	l2 m	Hsp m.	Hmin m	Hmax m	ρ (kg/m^3)	A (m^2)	G m/s^2	Δh m	V=q/A m/s	ΔP (kP)
8	52	48	6			13600	0.001962	9.81	4	0.0002	5.336
10	54	46	10			13600	0.001962	9.81	8	1.4157	10.672
12	55	45	13			13600	0.001962	9.81	10	1.6989	13.342
14	57	43	16			13600	0.001962	9.81	14	1.9821	18.678
16	60	40	19			13600	0.001962	9.81	20	2.2652	26.682
20	65.5	34.5	23			13600	0.001962	9.81	31	2.8315	41.358
22	68	32	25			13600	0.001962	9.81	36	3.1147	48.029
24	73	27	26			13600	0.001962	9.81	46	3.3922	61.371

Hs=5cm

10	52.5	47.5	7			13600	0.001962	9.81	5	1.415	6.670
11.5	55	45	9			13600	0.001962	9.81	10	1.628	13.342
12	56	44	10			13600	0.001962	9.81	12	1.698	16.009
15	60	40	16			13600	0.001962	9.81	20	2.123	26.683
18	62	38	17			13600	0.001962	9.81	24	2.548	32.019
20	68	32	19			13600	0.001962	9.81	36	2.831	48.029
22	71	29	21			13600	0.001962	9.81	42	3.114	56.034
26	77	23	24			13600	0.001962	9.81	54	3.681	72.044

Hs=6cm

9	53.5	46.5	7			13600	0.001962	9.81	7	1.2742	9.339
11	55	45	9			13600	0.001962	9.81	10	1.5573	13.342
12	56.5	43.5	11			13600	0.001962	9.81	13	1.6989	17.344
13	57.5	42.5	12			13600	0.001962	9.81	15	1.8405	20.012
15	63	37	16			13600	0.001962	9.81	26	2.1236	34.682
18	68.5	31.5	20			13600	0.001962	9.81	37	2.5484	49.363
22	72	28	21			13600	0.001962	9.81	44	3.1147	58.703
24	75	25	24			13600	0.001962	9.81	50	3.3978	66.708

Hs=8cm

8.5	53.5	46.5	9			13600	0.001962	9.81	7	1.2034	9.333
10.5	57.5	42.5		10	11	13600	0.001962	9.81	15	1.4865	20.012
15	62	38	12			13600	0.001962	9.81	24	2.1236	32.019
17.5	67	33	17			13600	0.001962	9.81	34	2.4776	45.361
18.5	68	32	19			13600	0.001962	9.81	36	2.6192	48.029
21	73	27	21			13600	0.001962	9.81	46	2.9731	61.371
24	75	25	23			13600	0.001962	9.81	50	3.3972	66.708
26	77	23	26			13600	0.001962	9.81	54	3.6810	72.044

Hs=9cm

9	53.5	46.5	10			13600	0.001962	9.81	7	1.2742	9.339
11	54.5	45.5	11			13600	0.001962	9.81	9	1.5573	12.002
12	57	43		11	14	13600	0.001962	9.81	14	1.6989	18.672
15	59	41		12	14	13600	0.001962	9.81	18	2.1236	24.012
17	65	35		14	15	13600	0.001962	9.81	30	2.4068	40.024
20	71	29				13600	0.001962	9.81	42	2.8315	56.034
22	73	27				13600	0.001962	9.81	46	3.1147	61.371
24	76	24				13600	0.001962	9.81	52	3.3978	69.37

Hs=10cm

9	54.5	45.5	11			13600	0.001962	9.81	9	1.2742	12.007
10	54.5	45.5		12	14	13600	0.001962	9.81	9	1.4157	12.007
12	56.62	43.38		12	16	13600	0.001962	9.81	13.24	1.6989	17.664
15	62	38		14	17	13600	0.001962	9.81	24	2.1236	32.019
20	69	31	17			13600	0.001962	9.81	38	2.8315	50.698
22	74	26	20			13600	0.001962	9.81	48	3.1147	64.039
24	79	21	24			13600	0.001962	9.81	58	3.3978	77.381
9	54.5	45.5	11			13600	0.001962	9.81	9	1.27420	12.007

Hs=12cm

10	54.5	45.5	14			13600	0.001962	9.81	9	1.4157	12.0072
11	55.5	44.5		14	16	13600	0.001962	9.81	11	1.5573	14.6757
13	57	43		15	19	13600	0.001962	9.81	14	1.8405	18.6782
15	60.5	39.5		17	21	13600	0.001962	9.81	21	2.1232	28.0172
18	67	33		18	22	13600	0.001962	9.81	34	2.5484	45.361
20	71	29		19	23	13600	0.001962	9.81	42	2.8315	56.034
24	75	25		18	25	13600	0.001962	9.81	50	3.3978	66.708

Hs=13cm

10	55	45	15			13600	0.001962	9.81	10	1.4157	13.3411	12
12	57	43		14	18	13600	0.001962	9.81	14	1.6989	18.6782	23
13	58	42		15	21	13600	0.001962	9.81	16	1.8405	21.3465	34
16	64	36		16	28	13600	0.001962	9.81	28	2.2652	37.3564	45.8
19	69	31		19	32	13600	0.001962	9.81	38	2.6899	50.6981	56
24	75	25	25			13600	0.001962	9.81	50	3.39789331	66.7081	66

Tables for the Glass beads for the (4.6mm), di=1.3cm

Hs=4cm

Q m^3/hr	l1 m	l2 m	Hsp m.	Hmin m	Hmax m	ρ (kg/m^3)	A (m^2)	G m/s^2	Δh m	V=q/A m/s	ΔP (kP)
10	52.5	47.5	5			13600	0.001966	9.81	5	1.4125	6.672
15	54	46	11			13600	0.001966	9.81	8	2.1147	10.673
20	57	43	14			13600	0.001966	9.81	14	2.8529	18.678
24	62	38	17			13600	0.001966	9.81	24	3.3905	32.019
30	67	33	19			13600	0.001966	9.81	34	4.2394	45.361

Hs=6cm

12	53	47	7			13600	0.001966	9.81	6	1.6953	8.004
17	55.5	44.5	11			13600	0.001966	9.81	11	2.4017	14.675
20	57.5	42.5	12			13600	0.001966	9.81	15	2.8255	20.012
24	60.5	39.5	15			13600	0.001966	9.81	21	3.3906	28.017
30	65.5	34.5	17			13600	0.001966	9.81	31	4.2382	41.356

Hs=8cm

12	53	47	9			13600	0.001966	9.81	6	1.6952	8.0042
15	54.5	45.5		10	14	13600	0.001966	9.81	9	2.1191	12.007
20	57.5	42.5		12	16	13600	0.001966	9.81	15	2.8255	20.012
25	60	40	16			13600	0.001966	9.81	20	3.5319	26.683
30	64	36	17			13600	0.001966	9.81	28	4.2382	37.356

Hs=10cm

12	53	47	12			13600	0.001966	9.81	6	1.6953	8.0049
16	55.5	44.5		12	16	13600	0.001966	9.81	11	2.2604	14.675
20	59	41		14	19	13600	0.001966	9.81	18	2.8255	24.014
26	62	38		15	20	13600	0.001966	9.81	24	3.6731	32.019
30	66.5	33.5		18	22	13600	0.001966	9.81	33	4.2382	44.027

Hs=12cm

12.5	53.5	46.5	13			13600	0.001966	9.81	7	1.7659	9.339
16.5	55.5	44.5		14	22	13600	0.001966	9.81	11	2.3310	14.675
20	58	42		14	28	13600	0.001966	9.81	16	2.8255	21.346
26	61.5	38.5		19	31	13600	0.001966	9.81	23	3.6731	30.685
30	65	35		20	24	13600	0.001966	9.81	30	4.2382	40.024

Tables for the Glass beads for the (.00393m) di=1.3cm

Hs=4cm

Q m^3/hr	l1 m	l2 m	Hsp m.	Hmin m	Hmax m	ρ (kg/m^3)	A (m^2)	G m/s^2	Δh m	V=q/A m/s	ΔP (kP)
9	52	48	6			13600	0.001966	9.81	4	1.2718	5.336
13	53.5	46.5	10			13600	0.001966	9.81	7	1.8364	9.332
19	57.3	43.5	14			13600	0.001966	9.81	13.9	2.6842	18.582
20	58.4	42.6	15			13600	0.001966	9.81	15.8	2.8255	21.079
26	63	37	18			13600	0.001966	9.81	26	3.6731	34.688
30	68	32	19			13600	0.001966	9.81	36	4.238294	48.02976

Hs=6cm

11	52.5	47.5	7			13600	0.001966	9.81	5	1.554041	6.6708
15	55	45	10			13600	0.001966	9.81	10	2.119147	13.3416
20	59	41	13			13600	0.001966	9.81	18	2.825529	24.01488
26	63.5	36.5	17			13600	0.001966	9.81	27	3.673188	36.02232
30	65	35	19			13600	0.001966	9.81	30	4.238294	40.0248

Hs=8cm

11	53	47	9			13600	0.001966	9.81	6	1.5542	8.004
14	54.5	45.5		9	12	13600	0.001966	9.81	9	1.9778	12.007
18	57.5	42.5		11	21	13600	0.001966	9.81	15	2.5429	20.012
20	58.7	41.3	12			13600	0.001966	9.81	17.4	2.8255	23.214
26	62	38	15			13600	0.001966	9.81	24	3.6731	32.019
30	65.7	34.3	17			13600	0.001966	9.81	31.4	4.2382	41.892

Hs=10cm

11	52.8	47.2	11			13600	0.001966	9.81	5.6	1.5540	7.471
13	53.8	46.2		11	14	13600	0.001966	9.81	7.6	1.8365	10.139
18	57	43		12	16	13600	0.001966	9.81	14	2.5422	18.678
20	59.5	40.5		14	17	13600	0.001966	9.81	19	2.8255	25.349
24	63	37		15	16	13600	0.001966	9.81	26	3.3906	34.688
30	68.5	31.5		19	21	13600	0.001966	9.81	37	4.2382	49.363

Hs=12cm

12	53	47		12	14	13600	0.001966	9.81	6	1.695	8.004
15	48.8	51.2		14	19	13600	0.001966	9.81	-2.4	2.119	-3.201
20	48.2	51.8		15	26	13600	0.001966	9.81	-3.6	2.825	-4.8029
26	63	37		16	41	13600	0.001966	9.81	26	3.673	34.6881
30	67	33		18	41	13600	0.001966	9.81	34	4.238	45.3614

Tables for the Glass beads for the size (.0034m) di=1.3cm

Hs=4cm

Q m^3/hr	l1 m	l2 m	Hsp m.	Hmin m	Hmax m	ρ (kg/m^3)	A (m^2)	G m/s^2	Δh m	V=q/A m/s	ΔP (kP)
9	52	48	5			13600	0.001966	9.81	4	1.278	5.33664
13	53	47	9			13600	0.001966	9.81	6	1.894	8.00496
16	55.4	44.6	13			13600	0.001966	9.81	10.8	2.2603	14.40893
20	58.6	41.4	16			13600	0.001966	9.81	17.2	2.8255	22.94755
24	62	38	18			13600	0.001966	9.81	24	3.390	32.01984
30	67.8	32.2	21			13600	0.001966	9.81	35.6	4.2382	47.4961

Hs=6cm

11	53	47	7			13600	0.001966	9.81	6	1.554	8.0049
14	54	46	9			13600	0.001966	9.81	8	1.973	10.6732
18	57.5	42.5	13			13600	0.001966	9.81	15	2.542	20.0123
20	59	41	15			13600	0.001966	9.81	18	2.825	24.0148
26	62.5	37.5	18			13600	0.001966	9.81	25	3.673	33.3533
30	67	33	21			13600	0.001966	9.81	34	4.238	45.3614

Hs=8cm

11	52.7	47.3	9			13600	0.001966	9.81	5.4	1.554	7.204
15	54.7	45.3		10	11	13600	0.001966	9.81	9.4	2.119	12.542
20	58.5	41.5	14			13600	0.001966	9.81	17	2.825	22.680
26	63.5	36.5	17			13600	0.001966	9.81	27	3.673	36.022
30	67.6	32.4	21			13600	0.001966	9.81	35.2	4.238	46.962

Hs=10cm

11	53	47		11	12	13600	0.001966	9.81	6	1.554	8.0049
15	54.8	45.2		11	16	13600	0.001966	9.81	9.6	2.119	12.8079
20	58.5	41.5		14	16	13600	0.001966	9.81	17	2.825	22.6802
26	62.8	37.2		18	19	13600	0.001966	9.81	25.6	3.673	34.154
30	67	33		21	22	13600	0.001966	9.81	34	4.238	45.3614

Hs=12cm

11.5	52	48		12	14	13600	0.001966	9.81	4	1.624	5.336
15	54.8	45.2		13	21	13600	0.001966	9.81	9.6	2.119	12.807
20	58.8	41.2		14	21	13600	0.001966	9.81	17.6	2.825	23.481
26	62	38		19	21	13600	0.001966	9.81	24	3.673	32.019
30	68	32		22	23	13600	0.001966	9.81	36	4.238	48.029

Tables for the glass beads of size (.00264m) di=1.3cm

Hs=4cm

Q m^3/hr	l1 m	l2 m	Hsp m.	Hmin m	Hmax m	ρ (kg/m^3)	A (m^2)	G m/s^2	Δh m	V=q/A m/s	ΔP (kP)
8	51.6	48.4	5			13600	0.001966	9.81	3.2	1.130	4.2692
11.5	53	47	10			13600	0.001966	9.81	6	1.6249	8.006
15	55	45	14			13600	0.001966	9.81	10	2.147	13.3462
20	59.2	40.8	19			13600	0.001966	9.81	18.4	2.825	24.5424
26	64.8	35.2	24			13600	0.001966	9.81	29.6	3.673	39.4911
30	69	31	27			13600	0.001966	9.81	38	4.238	50.6988

Hs=6cm

10	52.5	47.5	7			13600	0.001966	9.81	5	1.412	6.6703
12	53	47	9			13600	0.001966	9.81	6	1.695	8.0049
17	55.5	44.5	14			13600	0.001966	9.81	11	2.403	14.6757
20	59.5	40.5	16			13600	0.001966	9.81	19	2.825	25.3490
24	62	38	18			13600	0.001966	9.81	24	3.390	32.0198
30	69	31	23			13600	0.001966	9.81	38	4.238	50.6983

Hs=8cm

10	52.8	47.2	10			13600	0.001966	9.81	5.6	1.412	7.4712
15	54.8	45.2		11	12	13600	0.001966	9.81	9.6	2.119	12.8073
20	59	41	14			13600	0.001966	9.81	18	2.825	24.01433
26	64.6	35.4	19			13600	0.001966	9.81	29.2	3.673	38.9574
30	67.5	32.5	21			13600	0.001966	9.81	35	4.238	46.6956

Hs=10cm

10	52.5	47.5		11	12	13600	0.001966	9.81	5	1.4127	6.6708
14	54.3	45.7		12	14	13600	0.001966	9.81	8.6	1.9773	11.4737
18	57.6	42.4		13	14	13600	0.001966	9.81	15.2	2.5429	20.2792
20	59	41		16	17	13600	0.001966	9.81	18	2.8255	24.0148
26	63	37		19	20	13600	0.001966	9.81	26	3.6731	34.6881
30	70	30		24	25	13600	0.001966	9.81	40	4.2382	53.3664

Hs= 12cm

11	53	47		13	14	13600	0.001966	9.81	6	1.5540	8.0049
15	54.8	45.2		14	18	13600	0.001966	9.81	9.6	2.1191	12.8079
20	60	40		17	21	13600	0.001966	9.81	20	2.8255	26.6832
26	65	35		21	22	13600	0.001966	9.81	30	3.6731	40.0248
30	69.5	30.5		24	25	13600	0.001966	9.81	39	4.2382	52.0322

Table for the glass bead di=1.5 cm for (.0046m)

Q m^3/hr	l1 m	l2 m	Hsp m.	Hmin m	Hmax m	ρ (kg/m^3)	A (m^2)	G m/s^2	Δh m	V=q/A m/s	ΔP (kP)
12	51.5	48.5	5			13600	0.001966	9.81	3	1.6953	4.003
14	51.7	48.3	6			13600	0.001966	9.81	3.4	1.97787	4.5361
17	52.5	47.5	7			13600	0.001966	9.81	5	2.4017	6.6703
19	53	47	9			13600	0.001966	9.81	6	2.68425	8.0049
22	53.5	46.5	10			13600	0.001966	9.81	7	3.10808	9.3391
26	55.5	44.5	14			13600	0.001966	9.81	11	3.67318	14.6757
30	56.5	43.5	17			13600	0.001966	9.81	13	4.23829	17.3440
32	57.4	42.6	17			13600	0.001966	9.81	14.8	4.52084	19.7455
36	60	40	19			13600	0.001966	9.81	20	5.08595	26.6832

Hs=6

14	51.7	48.3	7			13600	0.001966	9.81	3.4	1.977	4.5361
15	52	48		7	8	13600	0.001966	9.81	4	2.119	5.3366
17	52.5	47.5		8	9	13600	0.001966	9.81	5	2.401	6.6708
20	53.4	46.6		8	10	13600	0.001966	9.81	6.8	2.825	9.0722
22	53.7	46.3		9	11	13600	0.001966	9.81	7.4	3.108	9.8727
24	54.3	45.7		10	11	13600	0.001966	9.81	8.6	3.390	11.4733
28	55.5	44.5				13600	0.001966	9.81	11	3.955	14.6757
30	57	43	11			13600	0.001966	9.81	14	4.238	18.6782
32	58	42	13			13600	0.001966	9.81	16	4.520	21.3465
34	58.5	41.5	15			13600	0.001966	9.81	17	4.803	22.6807
36	59.2	40.8	16			13600	0.001966	9.81	18.4	5.085	24.5485

Hs=8

14	52	48		9	10	13600	0.001966	9.81	4	1.9773	5.3366
18	52.8	47.2		9	14	13600	0.001966	9.81	5.6	2.5429	7.4712
20	53.3	46.7		9	17	13600	0.001966	9.81	6.6	2.8255	8.8054
22	54	46		8	18	13600	0.001966	9.81	8	3.1080	10.6732
26	56	44		12	17	13600	0.001966	9.81	12	3.6731	16.0099
30	56	44		14	17	13600	0.001966	9.81	12	4.2382	16.0099
32	57	43		14	16	13600	0.001966	9.81	14	4.5208	18.6782
36	58.5	41.5		17	19	13600	0.001966	9.81	17	5.0859	22.6807

Hs=10

13	52	48	11			13600	0.001966	9.81	4	1.836	5.3363
15	52	48		14	17	13600	0.001966	9.81	4	2.119	5.3366
18	52.9	47.1		14	21	13600	0.001966	9.81	5.8	2.542	7.738
20	53	47		16	21	13600	0.001966	9.81	6	2.825	8.0043
24	54	46		16	31	13600	0.001966	9.81	8	3.390	10.6733
28	54	46		14	51	13600	0.001966	9.81	8	3.955	10.6733
32	56	44		14	25	13600	0.001966	9.81	12	4.520	16.0099
36	57	43		17	22	13600	0.001966	9.81	14	5.085	18.6782

Hs=12cm

13.5	52	48	13			13600	0.001966	9.81	4	1.9072	5.336
16	52.5	47.5		17	19	13600	0.001966	9.81	5	2.2604	6.67084
18	53	47		16	26	13600	0.001966	9.81	6	2.5429	8.00496
22	53	47		17	25	13600	0.001966	9.81	6	3.1080	8.00496
24	54	46		17	36	13600	0.001966	9.81	8	3.3906	10.6732
36	55.5	44.5		22	55	13600	0.001966	9.81	11	5.0859	14.6757

Tables for di=1.5 cm for (.00393m) glass bead

Hs=4cm

Q m^3/hr	l1 m	l2 m	Hsp m.	Hmin m	Hmax m	ρ (kg/m^3)	A (m^2)	G m/s^2	Δh m	V=q/A m/s	ΔP (kP)
12	51.5	48.5	5			13600	0.001966	9.81	3	1.693	4.0024
14	51.6	48.4	6			13600	0.001966	9.81	3.2	1.977	4.26931
16	52	48	7			13600	0.001966	9.81	4	2.260	5.33664
20	52.5	47.5	8			13600	0.001966	9.81	5	2.825	6.6708
24	53.5	46.5	9			13600	0.001966	9.81	7	3.390	9.33912
28	54.5	45.5	13			13600	0.001966	9.81	9	3.955	12.007
30	55	45	14			13600	0.001966	9.81	10	4.238	13.3413
36	57.7	42.3	19			13600	0.001966	9.81	15.4	5.085	20.5460

Hs=6cm

11	51	49	7			13600	0.001966	9.81	2	1.554	2.6684
13.5	51.7	48.3	9			13600	0.001966	9.81	3.4	1.907	4.5365
18	52.6	47.4	10			13600	0.001966	9.81	5.2	2.542	6.9376
20	52.7	47.3	10.5			13600	0.001966	9.81	5.4	2.825	7.2044
24	53.6	46.4	12			13600	0.001966	9.81	7.2	3.390	9.6059
28	54.7	45.3	13			13600	0.001966	9.81	9.4	3.955	12.5413
32	56	44	15			13600	0.001966	9.81	12	4.520	16.0099
34	57.2	42.8	16			13600	0.001966	9.81	14.4	4.803	19.2119
36	58.5	41.5	17			13600	0.001966	9.81	17	5.085	22.6807

Hs=8cm

12	51.7	48.3	9			13600	0.001966	9.81	3.4	1.6953	4.5361
15	52	48		10	14	13600	0.001966	9.81	4	2.1191	5.3366
18	52.5	47.5		8	16	13600	0.001966	9.81	5	2.5429	6.6703
20	53	47		13	17	13600	0.001966	9.81	6	2.8255	8.0049
24	54	46		14	18	13600	0.001966	9.81	8	3.3906	10.6732
30	56	44		15	17	13600	0.001966	9.81	12	4.2382	16.0099
32	56.5	43.5		16	17	13600	0.001966	9.81	13	4.5208	17.3440
34	57.8	42.2		17	19	13600	0.001966	9.81	15.6	4.8034	20.8129

Hs=10cm

13	52	48		10	12	13600	0.001966	9.81	4	1.8365	5.3366
16	52.5	47.5		14	16	13600	0.001966	9.81	5	2.2604	6.6703
20	53	47		14	22	13600	0.001966	9.81	6	2.8255	8.0049
25	54	46		16	30	13600	0.001966	9.81	8	3.5319	10.6732
28	55	45		16	34	13600	0.001966	9.81	10	3.9557	13.3413
30	55.6	44.4		19	22	13600	0.001966	9.81	11.2	4.2382	14.9425
34	57.3	42.7		22	24	13600	0.001966	9.81	14.6	4.8033	19.4787
35	58	42		23	34	13600	0.001966	9.81	16	4.9446	21.3465

Hs=12cm

13	52	48	13	14		13600	0.001966	9.81	4	1.836	5.3366
16	52.4	47.6	15	20		13600	0.001966	9.81	4.8	2.2604	6.4039
20	53	47	16	24		13600	0.001966	9.81	6	2.8255	8.0049
24	54	46	17	34		13600	0.001966	9.81	8	3.3906	10.6732
30	56	44	19	50		13600	0.001966	9.81	12	4.2382	16.0099

Tables for di=1.5 cm, glass bead (.0034m) Hs=4cm

Q m^3/hr	l1 m	l2 m	Hsp m.	Hmin m	Hmax m	ρ (kg/m^3)	A (m^2)	G m/s^2	Δh m	V=q/A m/s	ΔP (kP)
10	51.4	48.6	5			13600	0.001966	9.81	2.8	1.412	3.7356
14	51.7	48.3	8			13600	0.001966	9.81	3.4	1.973	4.5361
18	52.7	47.3	9			13600	0.001966	9.81	5.4	2.542	7.2044
20	53.4	46.6	12			13600	0.001966	9.81	6.8	2.825	9.0722
22	53.8	46.2	13			13600	0.001966	9.81	7.6	3.108	10.1393
24	54.2	45.8	15			13600	0.001966	9.81	8.4	3.390	11.2069
28	56	44	17			13600	0.001966	9.81	12	3.955	16.0099
30	56.5	43.5	18.5			13600	0.001966	9.81	13	4.238	17.3440
34	58	42	20			13600	0.001966	9.81	16	4.803	21.3465

Hs=6cm

11	51.7	48.3	7			13600	0.001966	9.81	3.4	1.553	4.5361
12	51.8	48.2	8			13600	0.001966	9.81	3.6	1.695	4.80297
15	52	48	11			13600	0.001966	9.81	4	2.119	5.33664
20	52.7	47.3	13			13600	0.001966	9.81	5.4	2.825	7.20446
24	54	46	14			13600	0.001966	9.81	8	3.390	10.6732
28	55.5	44.5	16			13600	0.001966	9.81	11	3.955	14.6757
30	56.5	43.5	17			13600	0.001966	9.81	13	4.238	17.3440
32	57.6	42.4	18			13600	0.001966	9.81	15.2	4.520	20.2792
34	58	42	19			13600	0.001966	9.81	16	4.803	21.3465

Hs=8cm

12	52	48		10	11	13600	0.001966	9.81	4	1.695	5.3363
14	52.4	47.6		11	13	13600	0.001966	9.81	4.8	1.977	6.4039
20	53	47		12	14	13600	0.001966	9.81	6	2.825	8.0049
24	53.8	46.2		14	16	13600	0.001966	9.81	7.6	3.390	10.1396
28	55.6	44.4		17		13600	0.001966	9.81	11.2	3.955	14.9425
30	56.8	43.2		18		13600	0.001966	9.81	13.6	4.238	18.1445
32	57.8	42.2		19		13600	0.001966	9.81	15.6	4.520	20.8123
34	57.8	42.2		19		13600	0.001966	9.81	15.6	4.803	20.8129

Hs=10cm

11	51.8	48.2	11			13600	0.001966	9.81	3.6	1.554	4.8029
14	52.5	47.5		13	19	13600	0.001966	9.81	5	1.977	6.6703
18	53	47		13	21	13600	0.001966	9.81	6	2.542	8.0049
20	53.8	46.2		16	30	13600	0.001966	9.81	7.6	2.825	10.1396
28	55.4	44.6		17	26	13600	0.001966	9.81	10.8	3.955	14.4089
30	56	44		19	23	13600	0.001966	9.81	12	4.238	16.0099
32	58	42		20	26	13600	0.001966	9.81	16	4.520	21.3465
34	57.4	42.6		22	22	13600	0.001966	9.81	14.8	4.803	19.7455

Hs=12cm

12	52	48	13			13600	0.001966	9.81	4	1.695	5.3366
15	52.4	47.6		16	19	13600	0.001966	9.81	4.8	2.119	6.40396
18	53	47		17	30	13600	0.001966	9.81	6	2.542	8.0049
20	53.8	46.2		17	35	13600	0.001966	9.81	7.6	2.825	10.1396
26	55	45		19	40	13600	0.001966	9.81	10	3.673	13.341
20	56.6	43.4		20	30	13600	0.001966	9.81	13.2	2.825	17.6109
34	57.5	42.5		22	34	13600	0.001966	9.81	15	4.803	20.0122

Tables for the glass beads (.00264m), di=1.5 cm

Hs=4cm

Q m^3/hr	l1 m	l2 m	Hsp m.	Hmin m	Hmax m	ρ (kg/m^3)	A (m^2)	G m/s^2	Δh m	V=q/A m/s	ΔP (kP)
10	51.5	48.5	5			13600	0.001966	9.81	3	1.412	4.0024
14	51.8	48.2	8			13600	0.001966	9.81	3.6	1.977	4.8029
17	52.4	47.6	11			13600	0.001966	9.81	4.8	2.401	6.4039
20	53.5	46.5	13			13600	0.001966	9.81	7	2.825	9.3393
22	53.8	46.2	14			13600	0.001966	9.81	7.6	3.108	10.1393
24	54.4	45.6	16			13600	0.001966	9.81	8.8	3.390	11.7406
30	55.8	44.2	19			13600	0.001966	9.81	11.6	4.238	15.4762
34	57.5	42.5	22			13600	0.001966	9.81	15	4.803	20.012

Hs=6cm

10	51.6	48.4	9			13600	0.001966	9.81	3.2	1.412	4.2693
13	51.8	48.2	7			13600	0.001966	9.81	3.6	1.836	4.8029
16	52.4	47.6	11			13600	0.001966	9.81	4.8	2.260	6.4039
20	53.5	46.5	14			13600	0.001966	9.81	7	2.825	9.3391
24	55.4	44.6	16			13600	0.001966	9.81	10.8	3.390	14.4089
28	55.6	44.4	17			13600	0.001966	9.81	11.2	3.955	14.9425
30	58	42	18			13600	0.001966	9.81	16	4.238	21.3465
34	58	42	21			13600	0.001966	9.81	16	4.803	21.3465

Hs=10cm

11	51.8	48.2		10	11	13600	0.001966	9.81	3.6	1.554	4.8029
14	52.4	47.6		14	19	13600	0.001966	9.81	4.8	1.972	6.4039
18	53.4	46.6		14	36	13600	0.001966	9.81	6.8	2.542	9.0722
20	53.6	46.4		13	41	13600	0.001966	9.81	7.2	2.825	9.6059
24	54.4	45.6		14	43	13600	0.001966	9.81	8.8	3.390	11.740
28	55	45		20	24	13600	0.001966	9.81	10	3.955	13.341
30	56	44		21	24	13600	0.001966	9.81	12	4.238	16.009
34	57.5	42.5		24	27	13600	0.001966	9.81	15	4.802	20.012

Hs=12cm

11	51.8	48.2		13	14	13600	0.001966	9.81	3.6	1.554	4.8029
15	52.5	47.5		16	26	13600	0.001966	9.81	5	2.119	6.6708
18	53	47		16	44	13600	0.001966	9.81	6	2.542	8.0049
20	54	46		14	50	13600	0.001966	9.81	8	2.822	10.6732
24	54.5	45.5		15	49	13600	0.001966	9.81	9	3.390	12.0074
26	55	45		15	56	13600	0.001966	9.81	10	3.673	13.3416
30	56.6	43.4		22	26	13600	0.001966	9.81	13.2	4.238	17.6109
34	58	42		26	30	13600	0.001966	9.81	16	4.802	21.3465
36	59	41		38	32	13600	0.001966	9.81	18	5.085	24.0148

Table for the glass bead di=2cm for (.0046m)

Hs=4cm

Q m^3/hr	l1 m	l2 m	Hsp m.	Hmin m	Hmax m	ρ (kg/m^3)	A (m^2)	G m/s^2	Δh m	V=q/A m/s	ΔP (kP)
12	51.5	48.5	5			13600	0.001966	9.81	3	1.695	4.0023
14	51.7	48.3	6			13600	0.001966	9.81	3.4	1.977	4.5362
17	52.5	47.5	7			13600	0.001966	9.81	5	2.402	6.6703
19	53	47	9			13600	0.001966	9.81	6	2.684	8.0049
22	53.5	46.5	10			13600	0.001966	9.81	7	3.108	9.3391
26	55.5	44.5	14			13600	0.001966	9.81	11	3.673	14.6757
30	56.5	43.5	17			13600	0.001966	9.81	13	4.238	17.3440
32	57.4	42.6	17			13600	0.001966	9.81	14.8	4.520	19.7455
36	60	40	19			13600	0.001966	9.81	20	5.085	26.683

Hs=6cm

14	51.7	48.3	7			13600	0.001966	9.81	3.4	1.972	4.5361
15	52	48		7	8	13600	0.001966	9.81	4	2.119	5.3366
17	52.5	47.5		8	9	13600	0.001966	9.81	5	2.401	6.6708
20	53.4	46.6		8	10	13600	0.001966	9.81	6.8	2.825	9.0722
22	53.7	46.3		9	11	13600	0.001966	9.81	7.4	3.108	9.8727
24	54.3	45.7		10	11	13600	0.001966	9.81	8.6	3.390	11.473
28	55.5	44.5				13600	0.001966	9.81	11	3.955	14.6757
30	57	43	11			13600	0.001966	9.81	14	4.238	18.6782
32	58	42	13			13600	0.001966	9.81	16	4.520	21.3465
34	58.5	41.5	15			13600	0.001966	9.81	17	4.803	22.6807
36	59.2	40.8	16			13600	0.001966	9.81	18.4	5.085	24.5485

Hs=8cm

14	52	48		9	10	13600	0.001966	9.81	4	1.977	5.336
18	52.8	47.2		9	14	13600	0.001966	9.81	5.6	2.542	7.471
20	53.3	46.7		9	17	13600	0.001966	9.81	6.6	2.825	8.805
22	54	46		8	18	13600	0.001966	9.81	8	3.108	10.67
26	56	44		12	17	13600	0.001966	9.81	12	3.673	16.00
30	56	44		14	17	13600	0.001966	9.81	12	4.238	16.009
32	57	43		14	16	13600	0.001966	9.81	14	4.520	18.678
36	58.5	41.5		17	19	13600	0.001966	9.81	17	5.085	22.680

Hs=10cm

13	52	48	11			13600	0.001966	9.81	4	1.836	5.336
15	52	48		14	17	13600	0.001966	9.81	4	2.119	5.336
18	52.9	47.1		14	21	13600	0.001966	9.81	5.8	2.542	7.738
20	53	47		16	21	13600	0.001966	9.81	6	2.825	8.004
24	54	46		16	31	13600	0.001966	9.81	8	3.390	10.673
28	54	46		14	51	13600	0.001966	9.81	8	3.955	10.673
32	56	44		14	25	13600	0.001966	9.81	12	4.520	16.009
36	57	43		17	22	13600	0.001966	9.81	14	5.085	18.678

Hs=12cm

13.5	52	48	13			13600	0.001966	9.81	4	1.907	5.3369
16	52.5	47.5		17	19	13600	0.001966	9.81	5	2.260	6.6708
18	53	47		16	26	13600	0.001966	9.81	6	2.542	8.0049
22	53	47		17	25	13600	0.001966	9.81	6	3.108	8.0049
24	54	46		17	36	13600	0.001966	9.81	8	3.390	10.6732
36	55.5	44.5		22	55	13600	0.001966	9.81	11	5.085	14.6757

Tables for di=2cm for (.00393m) glass bead

Hs=4cm

Q m^3/hr	l1 m	l2 m	Hsp m.	Hmin m	Hmax m	ρ (kg/m^3)	A (m^2)	G m/s^2	Δh m	V=q/A m/s	ΔP (kP)
12	51.5	48.5	5			13600	0.001966	9.81	3	1.6953	4.0024
14	51.6	48.4	6			13600	0.001966	9.81	3.2	1.977	4.2693
16	52	48	7			13600	0.001966	9.81	4	2.2604	5.336
20	52.5	47.5	8			13600	0.001966	9.81	5	2.8255	6.6744
24	53.5	46.5	9			13600	0.001966	9.81	7	3.3906	9.3391
28	54.5	45.5	13			13600	0.001966	9.81	9	3.9557	12.007
30	55	45	14			13600	0.001966	9.81	10	4.2382	13.3478
36	57.7	42.3	19			13600	0.001966	9.81	15.4	5.0859	20.5460

Hs=6cm

11	51	49	7			13600	0.001966	9.81	2	1.554	2.6683
13.5	51.7	48.3	9			13600	0.001966	9.81	3.4	1.907	4.5361
18	52.6	47.4	10			13600	0.001966	9.81	5.2	2.542	6.9376
20	52.7	47.3	10.5			13600	0.001966	9.81	5.4	2.825	7.2044
24	53.6	46.4	12			13600	0.001966	9.81	7.2	3.390	9.6059
28	54.7	45.3	13			13600	0.001966	9.81	9.4	3.955	12.5433
32	56	44	15			13600	0.001966	9.81	12	4.520	16.0099
34	57.2	42.8	16			13600	0.001966	9.81	14.4	4.803	19.2113
36	58.5	41.5	17			13600	0.001966	9.81	17	5.085	22.6807

Hs=8cm

12	51.7	48.3	9			13600	0.001966	9.81	3.4	1.695	4.536
15	52	48		10	14	13600	0.001966	9.81	4	2.119	5.336
18	52.5	47.5		8	16	13600	0.001966	9.81	5	2.542	6.673
20	53	47		13	17	13600	0.001966	9.81	6	2.825	8.004
24	54	46		14	18	13600	0.001966	9.81	8	3.390	10.673
30	56	44		15	17	13600	0.001966	9.81	12	4.238	16.009
32	56.5	43.5		16	17	13600	0.001966	9.81	13	4.520	17.344
34	57.8	42.2		17	19	13600	0.001966	9.81	15.6	4.803	20.812

Hs=10cm

13	52	48		10	12	13600	0.001966	9.81	4	1.836	5.336
16	52.5	47.5		14	16	13600	0.001966	9.81	5	2.260	6.670
20	53	47		14	22	13600	0.001966	9.81	6	2.825	8.004
25	54	46		16	30	13600	0.001966	9.81	8	3.531	10.673
28	55	45		16	34	13600	0.001966	9.81	10	3.955	13.343
30	55.6	44.4		19	22	13600	0.001966	9.81	11.2	4.238	14.942
34	57.3	42.7		22	24	13600	0.001966	9.81	14.6	4.803	19.478
35	58	42		23	34	13600	0.001966	9.81	16	4.944	21.346

Hs=12cm

13	52	48	13	14		13600	0.001966	9.81	4	1.836	5.3366
16	52.4	47.6	15	20		13600	0.001966	9.81	4.8	2.260	6.4039
20	53	47	16	24		13600	0.001966	9.81	6	2.825	8.0049
24	54	46	17	34		13600	0.001966	9.81	8	3.390	10.673
30	56	44	19	50		13600	0.001966	9.81	12	4.238	16.009

Tables for di=2cm orifice, glass bead (.0034m)

Hs=4cm

Q m^3/hr	l1 m	l2 m	Hsp m.	Hmin m	Hmax m	ρ (kg/m^3)	A (m^2)	G m/s^2	Δh m	V=q/A m/s	ΔP (kP)
10	51.4	48.6	5			13600	0.001966	9.81	2.8	1.412	3.7356
14	51.7	48.3	8			13600	0.001966	9.81	3.4	1.973	4.5361
18	52.7	47.3	9			13600	0.001966	9.81	5.4	2.542	7.2044
20	53.4	46.6	12			13600	0.001966	9.81	6.8	2.825	9.0722
22	53.8	46.2	13			13600	0.001966	9.81	7.6	3.108	10.139
24	54.2	45.8	15			13600	0.001966	9.81	8.4	3.390	11.206
28	56	44	17			13600	0.001966	9.81	12	3.955	16.0099
30	56.5	43.5	18.5			13600	0.001966	9.81	13	4.238	17.3440
34	58	42	20			13600	0.001966	9.81	16	4.803	21.3465

Hs=6cm

11	51.7	48.3	7			13600	0.001966	9.81	3.4	1.554	4.5361
12	51.8	48.2	8			13600	0.001966	9.81	3.6	1.695	4.8029
15	52	48	11			13600	0.001966	9.81	4	2.119	5.336
20	52.7	47.3	13			13600	0.001966	9.81	5.4	2.825	7.2044
24	54	46	14			13600	0.001966	9.81	8	3.390	10.673
28	55.5	44.5	16			13600	0.001966	9.81	11	3.955	14.675
30	56.5	43.5	17			13600	0.001966	9.81	13	4.238	17.344
32	57.6	42.4	18			13600	0.001966	9.81	15.2	4.520	20.2793
34	58	42	19			13600	0.001966	9.81	16	4.803	21.3465

Hs=8cm

12	52	48		10	11	13600	0.001966	9.81	4	1.695	5.3366
14	52.4	47.6		11	13	13600	0.001966	9.81	4.8	1.973	6.40396
20	53	47		12	14	13600	0.001966	9.81	6	2.825	8.0049
24	53.8	46.2		14	16	13600	0.001966	9.81	7.6	3.390	10.1396
28	55.6	44.4		17		13600	0.001966	9.81	11.2	3.955	14.9425
30	56.8	43.2		18		13600	0.001966	9.81	13.6	4.238	18.1445
32	57.8	42.2		19		13600	0.001966	9.81	15.6	4.520	20.8129
34	57.8	42.2		19		13600	0.001966	9.81	15.6	4.803	20.8123

Hs=10cm

11	51.8	48.2	11			13600	0.001966	9.81	3.6	1.554	4.802
14	52.5	47.5		13	19	13600	0.001966	9.81	5	1.977	6.673
18	53	47		13	21	13600	0.001966	9.81	6	2.542	8.0049
20	53.8	46.2		16	30	13600	0.001966	9.81	7.6	2.825	10.1396
28	55.4	44.6		17	26	13600	0.001966	9.81	10.8	3.955	14.4089
30	56	44		19	23	13600	0.001966	9.81	12	4.238	16.0099
32	58	42		20	26	13600	0.001966	9.81	16	4.520	21.3465
34	57.4	42.6		22	22	13600	0.001966	9.81	14.8	4.803	19.7455

Hs=12cm

12	52	48	13			13600	0.001966	9.81	4	1.695	5.336
15	52.4	47.6		16	19	13600	0.001966	9.81	4.8	2.119	6.4039
18	53	47		17	30	13600	0.001966	9.81	6	2.542	8.004
20	53.8	46.2		17	35	13600	0.001966	9.81	7.6	2.825	10.139
26	55	45		19	40	13600	0.001966	9.81	10	3.6731	13.343
20	56.6	43.4		20	30	13600	0.001966	9.81	13.2	2.825	17.610
34	57.5	42.5		22	34	13600	0.001966	9.81	15	4.803	20.012

Tables for the glass beads (.00264m), di=2cm

Hs=4cm

Q m^3/hr	l1 m	l2 m	Hsp m.	Hmin m	Hmax m	ρ (kg/m^3)	A (m^2)	G m/s^2	Δh m	V=q/A m/s	ΔP (kP)
10	51.5	48.5	5			13600	0.001966	9.81	3	1.412	4.002
14	51.8	48.2	8			13600	0.001966	9.81	3.6	1.973	4.8029
17	52.4	47.6	11			13600	0.001966	9.81	4.8	2.401	6.4039
20	53.5	46.5	13			13600	0.001966	9.81	7	2.825	9.339
22	53.8	46.2	14			13600	0.001966	9.81	7.6	3.108	10.139
24	54.4	45.6	16			13600	0.001966	9.81	8.8	3.393	11.740
30	55.8	44.2	19			13600	0.001966	9.81	11.6	4.238	15.476
34	57.5	42.5	22			13600	0.001966	9.81	15	4.803	20.012

Hs=6cm

10	51.6	48.4	9			13600	0.001966	9.81	3.2	1.412	4.2693
13	51.8	48.2	7			13600	0.001966	9.81	3.6	1.836	4.8029
16	52.4	47.6	11			13600	0.001966	9.81	4.8	2.260	6.4039
20	53.5	46.5	14			13600	0.001966	9.81	7	2.825	9.3391
24	55.4	44.6	16			13600	0.001966	9.81	10.8	3.393	14.4089
28	55.6	44.4	17			13600	0.001966	9.81	11.2	3.955	14.9425
30	58	42	18			13600	0.001966	9.81	16	4.238	21.3465
34	58	42	21			13600	0.001966	9.81	16	4.803	21.3465

Hs=10cm

11	51.8	48.2		10	11	13600	0.001966	9.81	3.6	1.554	4.8029
14	52.4	47.6		14	19	13600	0.001966	9.81	4.8	1.977	6.4039
18	53.4	46.6		14	36	13600	0.001966	9.81	6.8	2.542	9.0722
20	53.6	46.4		13	41	13600	0.001966	9.81	7.2	2.825	9.6059
24	54.4	45.6		14	43	13600	0.001966	9.81	8.8	3.390	11.7406
28	55	45		20	24	13600	0.001966	9.81	10	3.955	13.3413
30	56	44		21	24	13600	0.001966	9.81	12	4.238	16.0093
34	57.5	42.5		24	27	13600	0.001966	9.81	15	4.803	20.0124

Hs=12cm

11	51.8	48.2		13	14	13600	0.001966	9.81	3.6	1.554	4.8029
15	52.5	47.5		16	26	13600	0.001966	9.81	5	2.119	6.6703
18	53	47		16	44	13600	0.001966	9.81	6	2.542	8.0049
20	54	46		14	50	13600	0.001966	9.81	8	2.825	10.6732
24	54.5	45.5		15	49	13600	0.001966	9.81	9	3.390	12.0074
26	55	45		15	56	13600	0.001966	9.81	10	3.673	13.3413
30	56.6	43.4		22	26	13600	0.001966	9.81	13.2	4.238	17.6103
34	58	42		26	30	13600	0.001966	9.81	16	4.803	21.3465
36	59	41		38	32	13600	0.001966	9.81	18	5.085	24.0148

Table 2

Δ(U)/Ums	Hs/Dc	di/dc	ρ_s/ρ_f	dp/Dc	product	R-exp	R-Cal	%dev
0.2	1.6	0.2	2227	0.0786	5.16E-09	1.21	1.183	2.199
0.3	1.6	0.2	2227	0.0786	5.91E-09	1.53	1.412	7.652
0.4	1.6	0.2	2227	0.0786	6.50E-09	1.59	1.602	-0.773
0.5	1.6	0.2	2227	0.0786	7.00E-09	1.65	1.766	-7.061
0.4	0.8	0.2	2227	0.0786	7.52E-09	1.65	1.939	-17.563
0.4	1.2	0.2	2227	0.0786	6.90E-09	1.54	1.733	-12.635
0.4	1.6	0.2	2227	0.0786	6.50E-09	1.46	1.602	-9.746
0.4	2	0.2	2227	0.0786	6.20E-09	1.34	1.506	-12.43
0.4	1.6	0.2	2227	0.0786	6.50E-09	1.46	1.602	-9.746
0.4	1.6	0.26	2227	0.0786	6.82E-09	1.5	1.708	-13.888
0.4	1.6	0.3	2227	0.0786	7.01E-09	1.59	1.769	-11.263
0.4	1.6	0.4	2227	0.0786	7.39E-09	1.65	1.897	-15.021
0.4	1.6	0.2	2805	0.0786	3.69E-09	1.46	0.762	47.757
0.4	1.6	0.2	2227	0.0786	6.50E-09	1.53	1.602	-4.725
0.4	1.6	0.2	1845	0.0786	1.03E-08	3.71	2.935	20.884
0.4	1.6	0.2	1601	0.0786	1.45E-08	7.45	4.632	37.819
0.4	1.6	0.2	2227	0.0932	6.18E-09	1.53	1.5016	1.852
0.4	1.6	0.2	2227	0.0786	6.50E-09	1.59	1.6023	0.773
0.4	1.6	0.2	2227	0.068	6.78E-09	1.65	1.6931	2.6163
0.4	1.6	0.2	2227	0.0528	7.29E-09	1.21	1.864	-54.083

ABINASH KUMAR

PERSONAL DETAILS

Date of Birth: 15 AUG 1982
Gender: Male **Marital Status:** Single

Correspondence Address: Abinash Kumar, s/o-Narendra Singh, Biraj Nagar, Lalpur

Ranchi, Jharkhand, pin-834001

E-mail: erabinashsingh@gmail.com

abinash.bits04@yahoo.co.in

Phone Number: 09778495728.

Languages Known: English, Hindi,Bhojpuri.

COURSE DETAILS

M.Tech Chemocal	Institute	University / Board	SGPA	Year of Passing
4th sem	NIT Rourkela	NIT Rourkela	awaited	2010
3rd sem	NIT Rourkela	NIT Rourkela	8.23	2009
2nd sem	NIT Rourkela	NIT Rourkela	8.00	2009
1st sem	NIT Rourkela	NIT Rourkela	7.54	2008
B.Sc. Engg(B.Tech)	**Institute**	**University / Board**	**Marks Obtained (%)**	**Year of Passing**
4th year	BIT Sindri	Vinoba Bhave	71.6	2008
3rd year	BIT Sindri	Vinoba Bhave	68.4	2007
2nd year	BIT Sindri	Vinoba Bhave	60	2006
1st year	BIT Sindri	Vinoba Bhave	62.25	2005
H.S.C	St. Xavier's college, Ranchi	B.I.E.C (Patna)	51.55	2000
S.S.C	Gossner high school, Ranchi	B.S.E.B (Patna)	68.24 (second topper)	1998

TECHNICAL SKILLS

- Ms-office.
- Knowledge in chemical equipment design.
- Basic knowledge in C.F.D. (computational fluid dynamics).

- gPROMS ,MATLAB, ANSYS

PROJECT (B.sc Engg.) & SUMMER TRAININNG

Coal properties and beneficiation, IOCL Barouni.

ONE DAY VISIT-coal washary (Dhanbad), ACC Cement, CFRI, Hindalko Muri

M.TECH PROJECT

Studies On Fluidization Behavior Of Spouted Bed And Mathematical Modeling.

SEMINAR

- Compact heat exchanger
- Reactive distillation with thermal coupling
- FUEL CELL, challenges in catalysis.
- Oxygen Sensor based on zirconium- cerium oxide

HOBBIES

- Acupressure and health care-treated more than 1000 people
- Interact with people
- Yoga and meditation
- Cartooning and Diary writing

RANK

BIHAR JEE(BCECE),DQ-GEN 29,

312 GATE AIR -1221 in 2008

GATE 76 PERCENTILE in 2010

CO-CURRUCULAR ACTIVITIES

Pres ntly working as secretary YOGA CLUB NIT ROURKELA

Served as program co-coordinator of Eco Club Bit Sindri

Regular publisment of letter to editor

Second prize winner in model presentation nit Patna

Class representative during Bs.c Engineering

OBJECTIVE

"To become an effective resource for the organization and to grow continuously on success curve with learning and improvement".

Signature

Date: __/__/

Place: Rourkela.