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Research Article

HYDRODYNAMICS OF A FLUIDIZED BED WITH A PARTITIONED DISTRIBUTOR

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ABSTRACT
The gas solid hydrodynamics in a fluidized bedwith partitioned concave distributor was investigated. The study included hydrodynamic characteristics and moving pattern of particles in the bed and elutriation of fine particles. The optimum air distribution ratio through the partitioned distributorwhich gives unique particle circulation pattern in the bed was experimentally arrived. The effects of variables, such as superficial gas velocity, bed material and bed height on elutriation rate constant for flat plate and concave distributor as well as for partitioned distributor are presented. Bed materials used are iso propylene and bed ash. The experimental results of elutriation have been used for developing dimensionless correlations of elutriation rate for the partitioned distributor.

Nomenclature

A_d, A_{or} = Area of distributor and orifice
A Ar = Archimedis number, $d_p^3\rho_g(\rho_p-\rho_g)g/\mu_g^2$
D = Reactor Diameter
d_p= Material particle size
d_p^* = Non dimensional Material particle size
g = Acceleration due to gravity
G_{mf}= Fluid mass velocity at minimum fluidization
Fr = Froude number
H_S = Static bed height
H_{mf} = Height of the bed at minimum fluidization
q1:q2:q3 =Air flow rate fraction through windbox
Re_{mf}= Reynolds No at minimum fluidizing velocity
Re_{dp} = Particle Reynolds number
ΔP_{mf}= Pressure drop at min. fluidizing velocity
ΔP_b = Bed pressure drop
ΔP_d = Distributor pressure drop
ΔP_t = Total bed pressure drop
T = Temperature
U_o = Superficial Gas velocity
U_{mf} = Minimum Fluidization Velocity
U^* = Non dimensional Fluid Velocity
μ_f = Viscosity of the fluid
ϕ_s = Sphericity of the particles
α = distributor apex angle
ε = Porosity of the bed
ε_{mf} = Voidage of bed at minimum fluidization
ρ_f = Density of the fluid
ρ_p, ρ_s = Density of the material used
BA = Bottom Ash
ISO = Iso-propylene

Key Words: *Hydrodynamics,Fluidization, Bubbling Regime, Bed Void Age, Conical Distributor, Flat Plate Distributor, Partitioned Distributor.*

Objective
The present study is to investigate the influence of partitioned distributor on the behaviour of fluidized bed using group B particles within the size range of 0.6 to 1mm covering bubbling regime. The partition distributor with three segments viz., flat plate followed by two numbers of conical distributors with apex angles of 90°, 120° respectively is used for experimentation. The bed voidage is used as the parameter for indicating the fluidization characteristics.

INTRODUCTION
IGCC is an emerging advanced clean coal technology wherein coal is converted to coal gas in a PFBG and combusted in gas turbine of a combined cycle power plant. To properly design a PFBG operating at

elevated pressure and temperature, there is a need to develop lab scale hydro dynamically similar cold model fluidized bed operating at ambient conditions which will simulate the desired hydrodynamic performance of commercial unit using selected type of distributor. In Pressurized Fluidized Bed Gasifier during gasification of low grade coal, the elutriation of un burnt carbon with fly ash is observed to be about 10-16% bringing down the carbon conversion efficiency. The reason for the same is attributed to bubble coalescence and breaking of large bubbles at the surface (splash zone) throwing out fines along with un burnt carbon at higher than the terminal velocity of particles (Davidson and Harrison,1971).while using conventional flat plate or conical type of distributors The elutriation is further expected to increase with increase in gasifier operating pressure (Geldart, 1972). One of the objective of this work is to investigate the influence of distributor types on the performance of fluidized bed reactors using group B particles as per Geldart, (1972) classification , with most particles of size 40 $\mu m < d_p < 500$ μm and density $1.4 < \rho_s$ .4 gm / cm^3covering bubbling regime . Many measures, such as circulation in bed and re- injecting fly ash into bed, etc, can be taken to improve above deficiency in performance. One of the effective methods of overcoming the problem is to use partitioned concave distributor instead of conventional flat plate or conical type of distributors This type of distributor with chosen configuration facilitates circulating movement of particles within the fluidized bed thus increasing fines residence time and improved carbon conversion efficiency.

The paper is treated in two fold , the first part is to investigate the influence of varying apex angle of the conical distributoron the hydrodynamic behavior of fluidized bed covering bubbling regime The first part of the experimental study is carried out using 100 mm ID cylindrical Perspex cold model (hydro dynamically scale down of 1.2 TPD –PFBG) with conical distributor. The bed void age measured for conical distributor is compared with flat plate distributor and results presented

The second part is to study the gas-solid hydrodynamic characteristics of partition distributor with three segments (flat plate followed by two numbers of conical distributors with apex angles of 90°, 120°) and present effects of various factors on particle trajectory and compare with commonly used conical and flat plate distributors.The paper presents the experimental study is carried out on 940 mm ID semi circular cold model (hydro dynamically scaled down model of 168 TPD-PFBG) with partitioned conical distributor .The parameters considered are varying flow rate fractions into each compartment and thus varying superficial velocity. The fluidization characteristics and particle moving trajectory in the bed were observed and photographed. The expanded bed height and bubble size were measured for each of the test conditions.. The bed void age is used as the parameter for indicating the fluidization quality in selecting the final configuration of the distributor

Gas - solid hydrodynamic characteristics with partitioned concave distributor and effects of various factors on particle elutriation are discussed in the paper and compared with the conical and flat plate distributors commonly used.

Experimental Set up

A perspex three dimensional semicircular test rig reactor of ID 940mm hydrodynamically scale down model of 168 tpd – PFBG plant is shown in Figure 1a. The scaling relations are used to arrive at the particle density. The scale factor (m) of two thirds is chosen and accordingly the bed diameter, expanded bed height and other hydrodynamic parameters have been fixed for the test rig. It is found that isopropylene material with a density of 925 kg/m^3 for cold model tests is hydrodynamically similar to hot model conditions. Three types of distributors viz., flat plate, conical and partitioned distributor have been used and hydrodynamically investigated. The general arrangement drawing of partitioned distributor is shown in Figure 1b. The first segment of partitioned distributor is a flat plate followed by conical distributor of lower apex angle of 90° with final segment of concave distributor having included angle of 120°.

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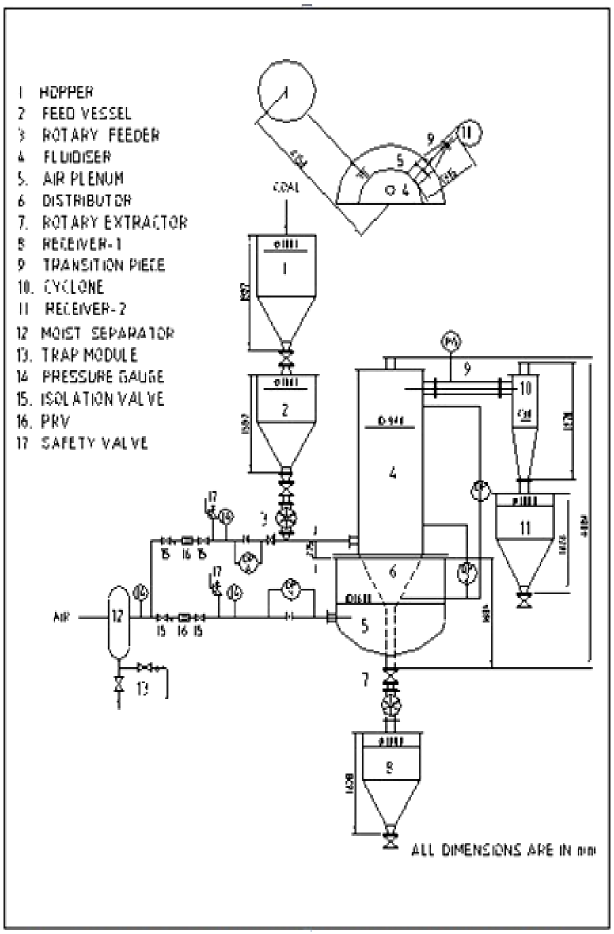

Figure 1(a): General Arrangement of Semi circular Test Rig

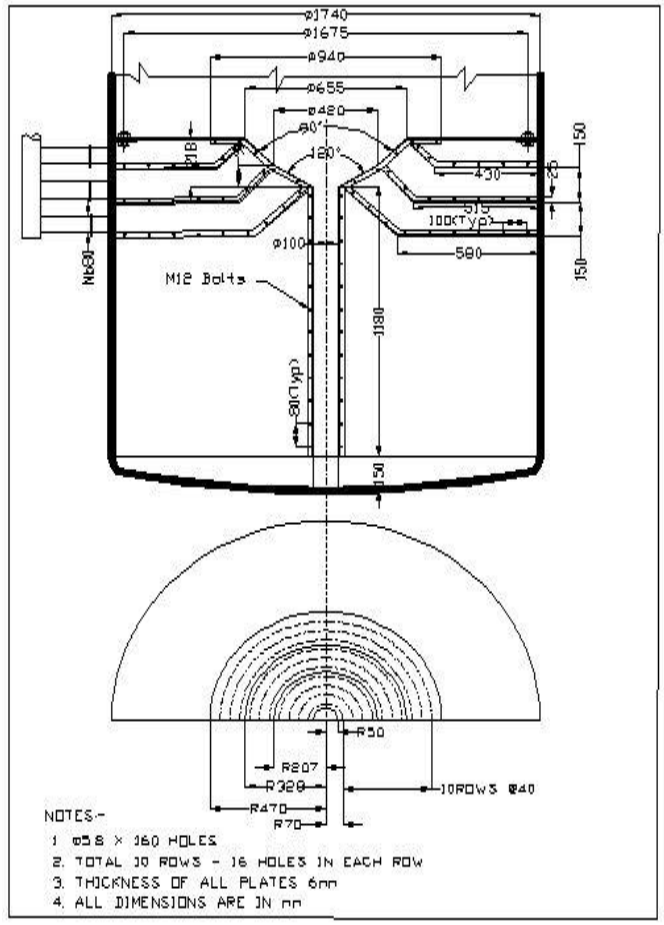

Figure 1(b): General Arrangement of Partitioned Distributor of Semi circular Test Rig

Flat Plate Distributor

Many types of distributors have been developed to improve the gas distribution in a fluidized bed. The choice of distributor is governed by the process and the operating conditions. The multi-orifice plate is the simpliest gas distributor used in industries. Its ease of construction and maintenance makes it a common choice.Further the bubble-cap type of orifice have been specially designed to prevent the back-flow of solids through the distributor. However, the quality of fluidization is not necessarily superior to the simpler multi-orifice plate. In a fluidized bed the distributor plate must be designed to offer uniform fluidization through the bed cross section. Uniform fluidization is achieved only if the distributor plate imposes a resistance to the total flow sufficient to over-come the fluids inherent resistance to rearranging and redistributing itself. Hence for proceeding with design and sizing of a distributor, the pressure drop across the distributor has to be assumed. The usual practice is to assume the distributor loss as a fraction of the bed pressure loss. Many investigations show that a ratio of distributor loss to bed pressure loss of about 0.3 to 0.4 has been recommended. The flat plate distributor is shown in Figure 2with ID of about 940mm and is provided with 10 rows,each row consisting of 16 equispaced holes of diameter 5.7mm.

Concave Distributor

In a fluidized bed with a concave distributor a different flow pattern is observed. In view of different bed heights on inclined plates lead to different pressure drops across the bed more gas tends flowing through the region where bed material layer is thinner. Less gas passes through the central zone where bed material layer is thicker. As a result, acted by gravity, buoyance and drag force, the particles in the central zone move down wards and the particles at both sides between the central zone and wall zone flow upwards rapidly.

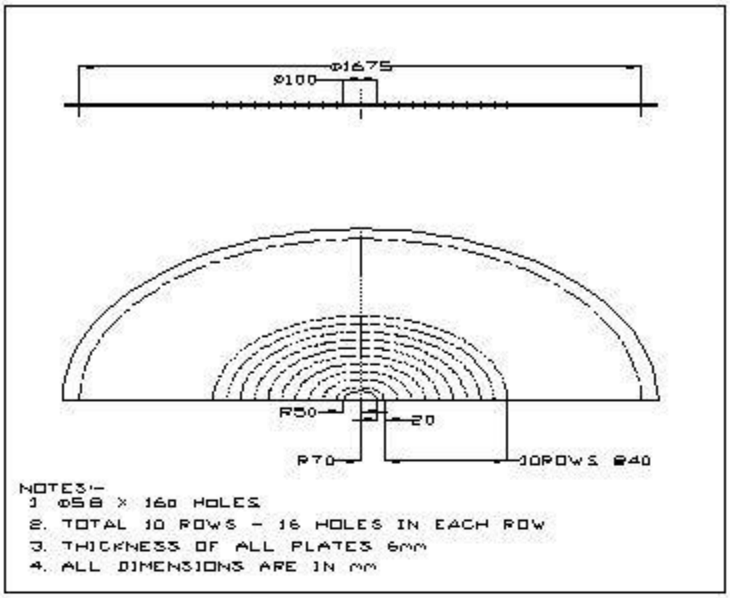

Figure 2: Flat Plate Distributor of Semi circular Test Rig

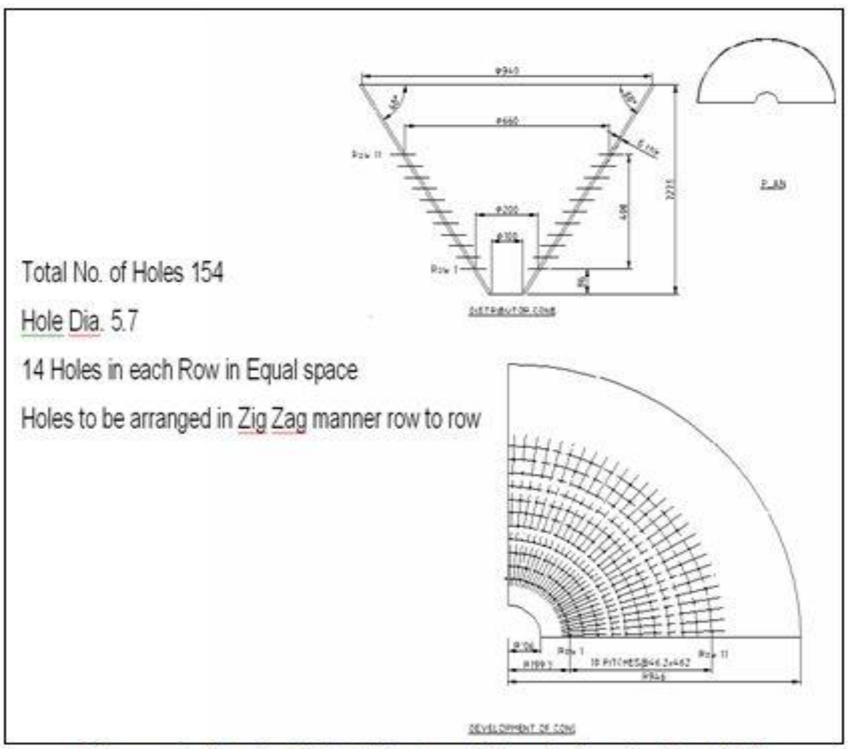

Figure 3: Conical Distributor of Semi circular Test Rig

Once reaching the bed surface, most of them turn to central zone and then move downwards, the others turn to the wall zone and move downwards along the wall. Two different particle circulations formed in the bed, the big one in the center and the small one in the wall zone. The distributor for the cold model is designed to have equivalent kinetic energy factor (α) to the orifices and the number of holes is arrived to be 160 The conical distributor is shown in Figure 3 and is provided with 10 rows, each row consisting of 16 equispaced holes of diameter 5.7mm arranged in a zigzag manner at a pitch of 40mm between each row.

Comparison of Flat Plate and Conical Distributor

The data has been recorded by carrying experiments with ‘sand’ and ‘bottom ash’ of mean particle sizes-0.8 mm at different bed heights using conical distributors with varying apex angles. (α) from 60^0 to 120^0 and repeated with Flat plate Distributor (apex angles. of 180^0) . The data is then used to find the bed void age derived using Ergun’s equation (1).

$$\Delta P_{mf} = H_{mf} (1-\epsilon_{mf}) (\rho_p-\rho_f) \quad ------------ \quad (1)$$

The bed void age obtained from equation is tabulated as shown at table 2. The bed void age is observed to decrease with the increase in distributor apex angle while, U_{mf} is found to be increasing .As the bed void age is indicative parameter for quality of fluidization, the results of cold model studies shows that Flat plate distributor is superior to conical distributor. However it may be noted that flat plate distributor has the disadvantage of forming single large bubble due to bubble coalescence which will lead to plug flow through the reactor This has negative effect on gasifier performance due to increase of elutriation of carbon particles resulting in lower overall carbon conversion efficiency. Therefore the conical distributor with 60^0 apex angle is advisable from ease of extracting the solids from fluidized bed gasifiers as well as for better back mixing.

Partitioned Concave Distributor

The general arrangement drawing of partitioned distributor is shown in Figure 1b. The first segment of partitioned distributor is a flat plate followed by conical distributor of lower apex angle of 90° with final segment of concave distributor having included angle of 120°. Thus the wind box is divided into three compartments for providing each compartment with air individually. The materials used are iso-propylene and bed ash Air at ambient temperature was used as fluidizing medium.

By operating the valve system at inlet, the flow through each passage leading to each of the compartment in the distributor can be varied and the bed dynamics can be changed to achieve better circulation pattern within the bed.

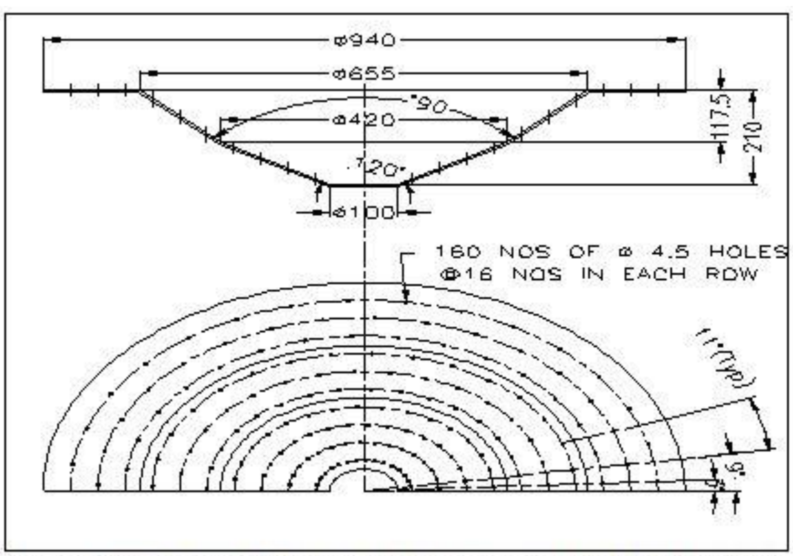

Figure 4(a): Partitioned Concave Distributor of Cold Model Test Rig

Figure 4(b): Photograph of Semi Circular Cold Model Test Rig With Partitioned Concave Distributor – Air Supply System

In the partitioned distributor flow through distributor the total in flow is divided into three streams as shown in Figure 4.a and 4.b. By operating the valve system at inlet, the flow through each passage leading to each of the compartment in the distributor can be varied and the bed dynamics can be changed to achieve better circulation pattern within the bed. As shown in the figure, the first segment of distributor is a flat plate followed by conical distributor of lower apex angle of 90° with final segment of concave distributor having included angle of 120°. Thus the windbox is divided into three compartments for providing each compartment with air individually. Air at ambient temperature was used as fluidizing medium. The materials used were isopropylene and bed ash and their physical properties are given in Table 1.

Table 1: Physical Properties of Materials

	Isopropylene	**Bed ash**
d_b mm	1.009	0.20-6.0
Φ_s	1.0	0.62
ρ_m Kg/m^3	425	1052
ρ_s Kg/m^3	900	2308

Experimental Procedure

By maintaining same particle size distribution of bed material, experiments were conducted with varying flowrate fractions into each compartment and thus varying superficial velocity. The fluidization characteristics and particle moving trajectory in the bed were observed and drawn graphically. The expanded bed height and bubble size were measured for each of the test conditions. Figure 5depicts gas-solids flow pattern for different groups of air distributions in the bed with the partitioned distributor.

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Thefines elutriated from the bed are collected with cyclone. Elutriation experiments were conducted with differentmaterials. Thesuperficial velocity, size of coarse particles and static bed height are used as variables to arrive at the elutriation rate constant.

For a partitioned concavedistributor provided with three different compartments, when air flowing through individual compartments varies in the ratio of q1:q2:q3, the distance between two peaks of the bed surface and the intensity changes and the particle circulation are found to be different. The size and

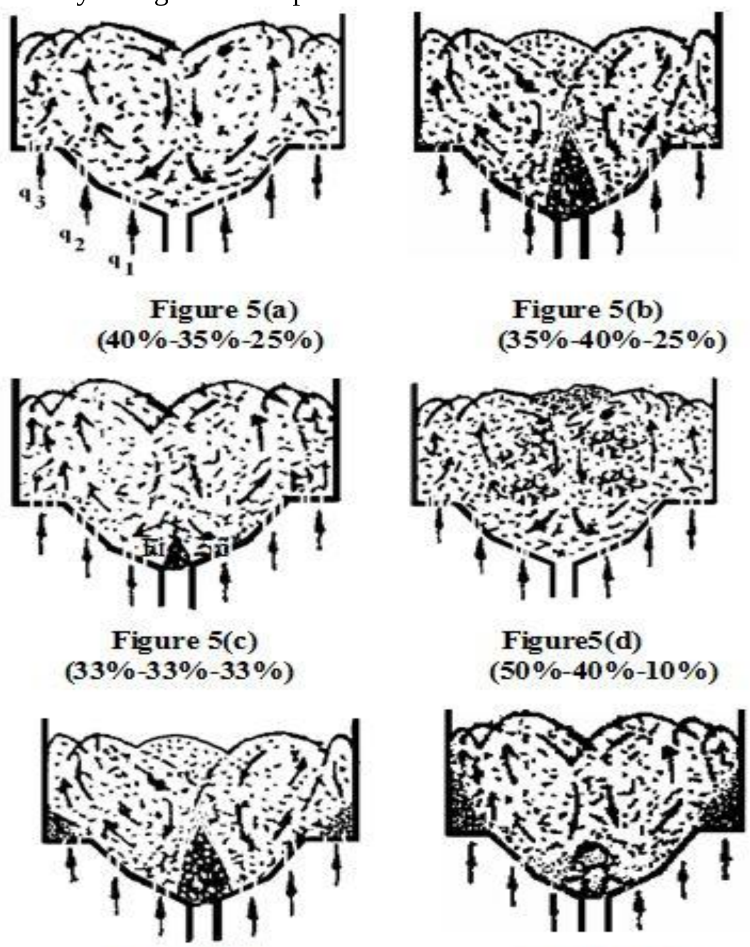

Figure 5(a) **(40%-35%-25%)**
Figure 5(b) **(35%-40%-25%)**
Figure 5(c) **(33%-33%-33%)**
Figure5(d) **(50%-40%-10%)**
Figure 5(e) **(20%-50%-30%)**
Figure 5(f) **(45%-55%-00%)**

Figure 5: Variation of particle circulation in the bed at different air distributions

the location of defluidizing zone are also changed.The following flow pattern of particle circulation is observed:

a) The more the air fraction (q1) passing through the central zone, the smaller the defluidizing zone in the center of the bed and the peaks of expanded bed surface approach the center..This condition of operation results in smaller circulating zone of particles.

b) On the other hand, if q1 passing through the central zone is toolarge, and air fraction q2 through mid channel is too small, it will be possible for a channeling flow to take place in the region.

c)In case of higher gas velocity on the inclined plates and more air fraction through middle channel (q2)the central dead zone will be enlarged, as shown in Figure 5 (b) and (e).when the bed height is shallower, this operating conditions also shortens the path of circulating movement of particles besides reducing the utilization factor of overall bed volume.

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d)The experiments show that for the air flow distribution of 40:35:25, no defluidizing zone is found in the bed as shown Figure 5 (a)and the circulating movement of particles was intense and is ideal condition.

The particle circulation pattern in the bed at different air flow ratios selected for experimentation are shown in Figure5 (a) to5(f). and the results are given in table 2. From the Figure5(e) to 5(f) we observe the stagnation zones near the two side walls and at the central zone of the bed. Also in Figure5(d) and 5(f) whenthe flow ratios q1 and q2 are more, and the air flow ratio passing through horizontal plate (q3) being less,it is observed that the particles will circulate from the central zone formingthe defluidizing zone at two side walls. In the Figure5(c) and 5(e) when the air flow ratio q1 is comparatively smaller to enable circulation of particles leads to formation of stagnation zone at the central part of the bed.

Therefore, optimal air flow distribution for the chosen partitioned distribution configuration is found to be of 40:35:25 by inspecting the circulation pattern and for the flow condition ensuring no defluidizing zones in the bed.The bed voidage is computed as given below and is arrived by measuring pressure drop using data acquisition system.

$$\epsilon_{mf} = [\rho_s / (\rho_s - \rho_g)] - [\Delta P_{1-2} / g * \rho_s - \rho_g)] * \Delta h_{1-2} \text{-------} \qquad (2)$$

Besides the results of partition distributor in ther form of computed bed voidages are given at table 3.

Table 2: Comparison of voidage (Єmf) for Conical and Flat plate Distributor

Material	Apex angle of conical /Flat plate Distributor	Bed Voidage of Cylindrical Reactor
Sand	60^0	0.5089
	120^0	0.4862
	150^0	0.466
	Flat plate 180^0	0.4451
Bottom ash	60^0	0.6504
	120^0	0.6178
	150^0	0.6071
	Flat plate 180^0	0.5983

Table 3: Experimental results of semi circular cold model test rig with partitioned concave distributor

Case No	**1**	**2**	**3**	**4**	**5**	**6**
Flow Ratio.	40:35:25	35:40:25	33:33:33	50:40:10	20:50:30	45:55:00
Distributor DP,mmWc	450	370	450	325	456	385
Total DP, mmWc	882	761	959	810	919	798
Bed DP,mmWc	432	391	510	486	464	413
Bubble size,cm	35	38	27	24	19	30
Bubble frequency,(1/S)	1.25	0.7	2	1.5	1.5	0.6
Density of gas, Kg/m^3	1.2	1.2	1.2	1.2	1.2	1.2
Density of particle,Kg/m^3	900	900	900	900	900	900
Bed Voidage	0.6296	0.6499	0.579	0.6092	0.5824	0.644
Expanded bed height,cm	166	159	172	177	158	165

From the parameters it is observed that fluidization qualityis improved by partition distributor and optimal air flow distribution for the chosen partitioned distribution configuration is found to be in the ratio of 40:35:25 .

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Results Of Cold Model Experimentation On 940 mm ID Semi Circular Test Rig

By maintaining same PSD of bed material, experiments were conducted with varying flow rate fractions into each compartment and thus varying superficial velocity. The fluidization characteristics and particle moving trajectory in the bed were observed and photographed. The expanded bed height and bubble size were measured for each of the test conditions.

Besides , the hydro dynamic .parameters of partition distributor are measured and graphically presented as (a) Froude no versus bubble rise velocity and (b) Bubble diameter versus bubble rise and given at Figure 6 & 7 respectively. The parameters are also compared with conical and flat plate distributor and it is observed that the fluidisation quality is improved by adopting partition distributor.

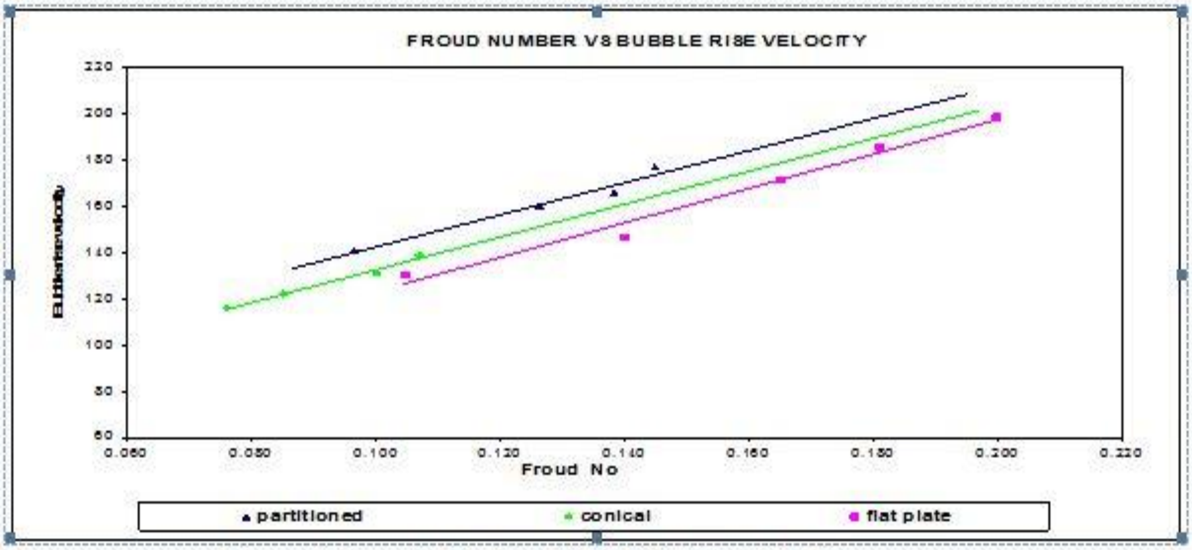

Figure 6: Froude Number Vs Bubble Rise Velocity

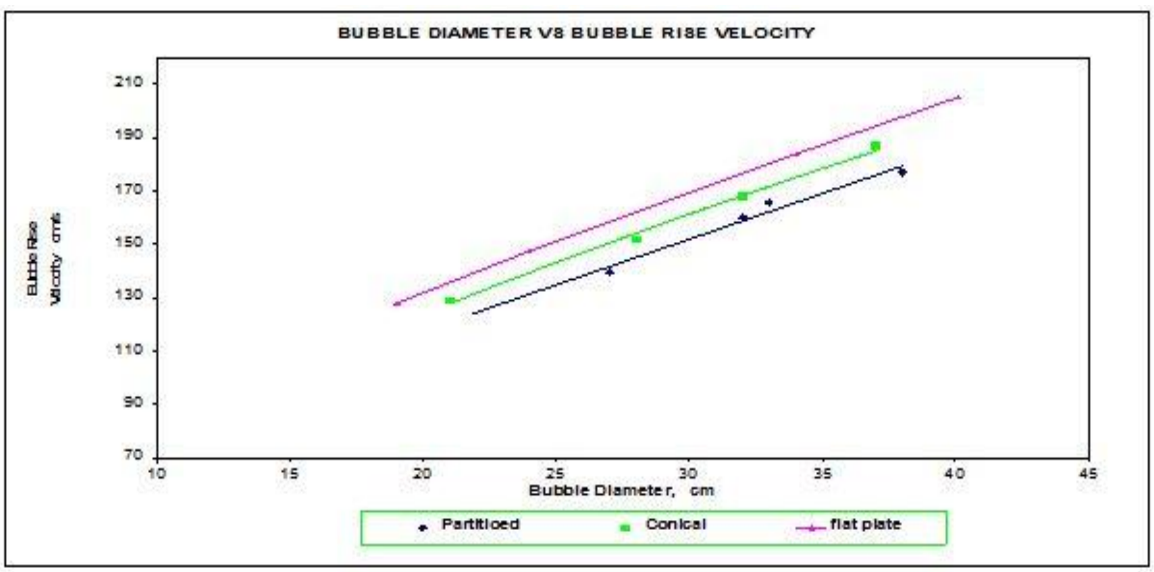

Figure 7: Variation of Bubble Diameter with Bubble Rise Velocity

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Elutriation Study

The effects of several variables, such as superficial gas velocity, bed material and bed heights on elutriation rate constants were investigated for flat plate and concave distributor as well as for partitioned distributor and given below.

Effectof gas velocity. The resulting force acting on a particle fluidized in the bed can be represented by,

$$F = \pi/8g\ \rho_g\ U_{of}^2\ d_p^2\ \pi/6\ (\rho_s - \rho_g)\ d_p^3 \quad \text{-------} \quad (3)$$

Equation (3) shows that superficial gas velocity U_{of} has a great effect on particle elutriation.

The variation of Elutriation(k) withsuperficial gas velocity (U_{of})for Partitioned Distributor. At different bed heights curves indicate that as the velocity increased, the particle elutriation increases sharply, and the effect for both the materials are the same. The relationship can be well represented with a power function given in Equation (4).

$$K = A\ U_{of}^m \quad \text{-------} \quad (4)$$

Exponent 'm' varies with the density and the size of fines. The results indicate that the greater the H/D ratio, the greater the exponent 'm'. as shownin table 4.Figure 8 represents the variation of elutriation rate constant with gas velocity for Partitioned, conical and flat plate distributors for bed ash material and partitioned distributor is better from elutriation point of view.

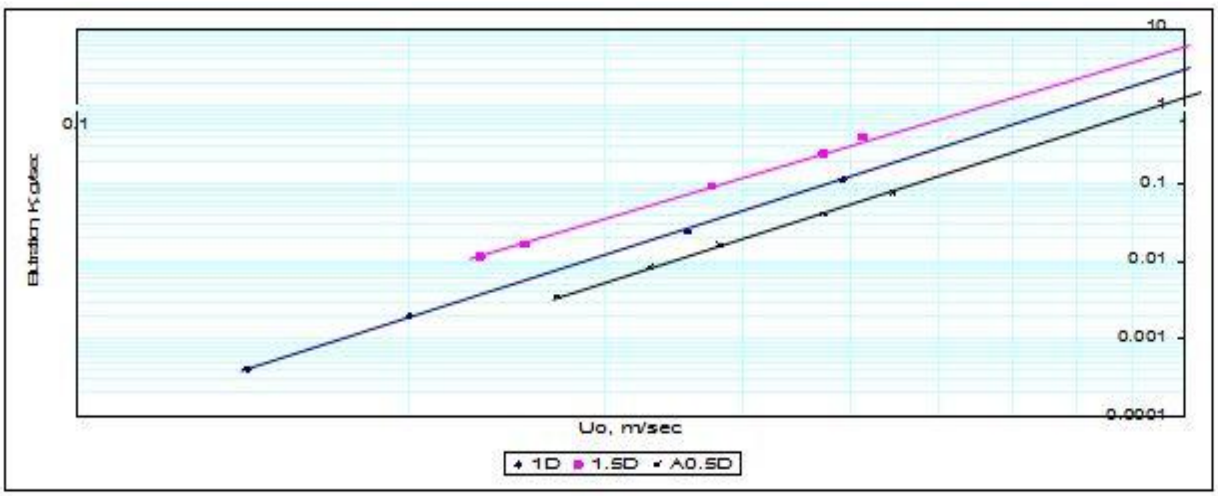

Figure 8: Variation of Elutriation K vs U_{of} For Partitioned Distributor At Different Bed Heights

Table 4: Bed ash constants for 'U_{of} to k' at different bed heights

H/D	A	m
0.5D	1.4	0.2646
1D	3	0.3111
1.5D	5.8	0.9045

Fluidization theory indicates elutriation does not take place until superficial velocity is greater than terminal velocity of particles. It was found in the experiments that a few fine particles were elutriated from the bed when U_{of} was less than U_t. The reason is the sizes of fines between two adjacent screens are not identical and gas velocity distribution across the freeboard section is not uniform. The calculation shows that the minimum superficial velocity at which the elutriation is at the very onset is just about the terminal velocity of the finest particle of them. It demonstrates that the excess gas velocity ($U_{of} - U_t$)

express carrying over capacity of the gas stream (Leva, 1951). TheFigure 9indicates the relationship between elutriation rate constant and excess velocity ($U_{of} – U_t$) and there appears a perfect power function relationship as given in Equation (5).

$$K = b\,(U_{of} – U_t)^{n} \text{ -------} \qquad (5)$$

In this condition the value of component n approaches a constant and does not vary with the density and the size of fines. The values of ‘n’ for bed ash at different bed heights are given in table 5. It shows that ($U_{of} – U_t$) can be chosen as a factor in deriving the correlations. Compared to flat plate and conical

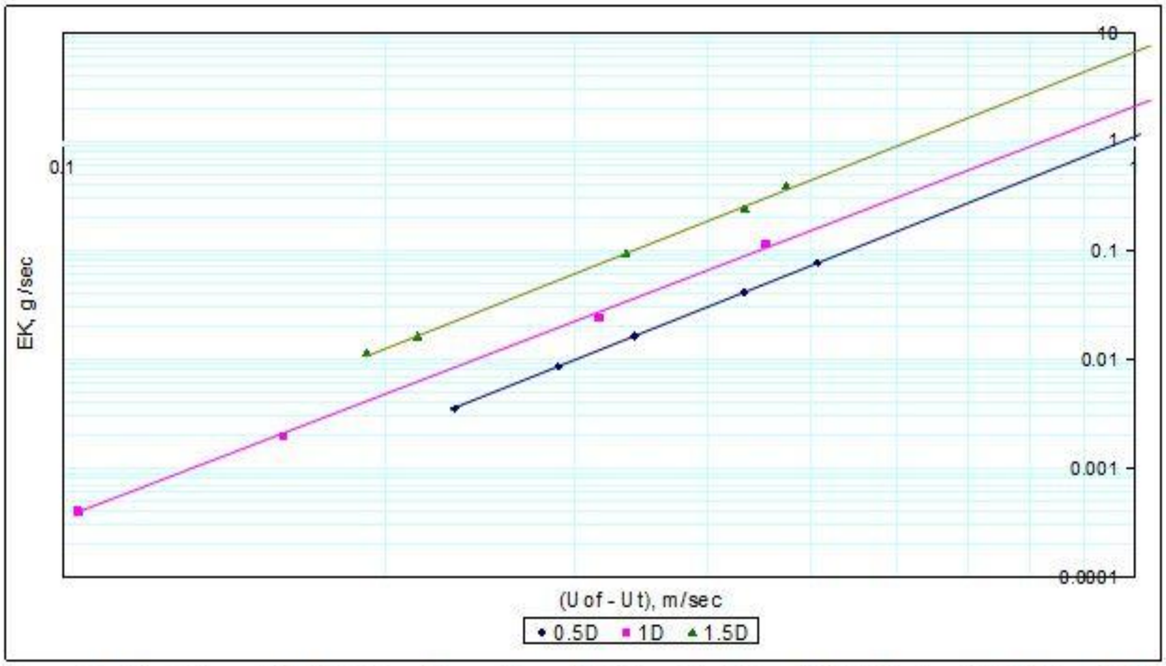

Figure 9: Variation of Elutriation K vs (U_{of} – U_t) For Partitioned Distributor At Different Bed Heights

distributor, the partitioned distributor seem to be having an added advantage that the bed voidage is lower due to smaller bubble sizes, besides having more residence time.

Table 5: Bed ash constants for ‘($U_{of} – U_t$) to k’ at different bed heights

H/D	b	n
0.5D	1.2	0.2646
1D	2	0.3111
1.5D	6.5	0.9045

Effect of particle size

The variation of particle diameter changes its terminal velocity directly, and thus the driving force of elutriation. As the diameter of the fines decreases, the amount of elutriated particles increases drastically. So, gas velocity is the most important factor affecting elutriation in the gas phase (Yong, 1985). The effect of the fines diameter is the most important parameter in the solid phase. As particle diameter of bed materials increases, void between particles increases and the fines are transported from internal zone through the voids to the bed surface more easily and the elutriation rate constant becomes greater (Wen and Hashinger, 1960).Within the size of particles used in the experiments, the relationship between the terminal velocity U_t and the particle diameter d_p is given in equation (6).

$$U_t = 0.153 d_p^{1.14} g0.0.71 (\rho_s - \rho_g)^{0.71} \text{-------} \quad (6)$$

CONCLUSION

The bed void age obtained from Ergun's equation decreases with the increase in distributor apex angle. It can be inferred that the flat plate distributor has marginal advantage over conical distributor. However from ease of extraction of bottom ash in PFBG, the conical distributors are being preferred over flat plate as this will also overcome stagnation zones which are likely to be formed at the side wall of the flat plate distributor. Besides flat plate Distributor has the disadvantage of forming single large bubble due to bubble coalescence which will lead to formation of slugs through the reactor.

The particle circulation was observed in the semi-circular cold model of fluidized bed with partitioned concave distributor. The residence time of fine particles in the bed has increased by adopting this type of distributor which is helpful in reducing the un burnt carbon and increasing overall carbon conversion efficiency.

The experimental results and the correlations derived show that the excess gas velocity and the fines size have strong effects on the elutriation rate constant. The fluidizing gas velocity and the particle size are to be selected with careful consideration in order to decrease the amount of fines elutriated from the bed.

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