size and density [16,17]. In group A, the particles with small size (d_p=30-150 µm) and having densities in range of <1500 kg/m^3 are classified. In group B, the particles with large size (d_p=150-500 µm) and having densities in range of <1500 kg/m^3 are classified. In group C, the particles with very small size (d_p<30 µm) and having low sphericity e.g., talc are classified. These particles are not easy to fluidize and they give rise to channeling more often. In group D, these particles are either of very large size or more denser e.g., lead shot [9]. Semolina Particles belongs to the B group particles because semolina particles size ranges from 200-450 µm [16]. We used the semolina particles of size 300 µm for this work.

Regimes of fluidization

In hydrodynamics studies of two phase liquid solid fluidized bed, the most significant factor is the contacting regime. In the perspective of Fluidization, hydrodynamics is the study of behavior of bed when fluid is passed through it at varying flow rates. In liquid, fluidized beds, the flow regimes are limited as compared to gas fluidized beds. Flow regimes in the two phase (liquid-solid) fluidized system mainly depends upon the liquid velocity. By increasing the fluid (liquid) velocity which is defined as liquid superficial velocity, the two phase (liquid-solid) system will undergo different flow regimes [10]. Bed remain intact when liquid velocity (U_l) is lower than that of the minimum fluidizing velocity (U_{mf}). When liquid superficial velocity is increased further than the min. fluidization velocity, then the two-phase liquid solid system enters into the regime of conventional fluidization, where exist clear and obvious boundary between the dense region (at bottom) and freeboard region (at top). In that regime, the increasing liquid velocity causes the denser phase to expand further and consequently the denser-dilute phase boundary is raised. As the velocity if liquid is further increased, the denser-dilute phase boundary becomes hazy (unclear) and as a result the height of the denser phase is increased. And few particles start to get entrained out of the solid particles bed. At this stage, the two-phase fluidized bed is shifted from conventional to the circulating fluidized bed [11]. By increasing the liquid solid density ratio, this transitions becomes more clear. When velocity of liquid becomes sufficiently high, huge quantity of particles are entrained out of the solid particles bed and solids circulation rate become increased sharply. Figure 1 shows the map of solid bed transition into different flow regimes. And the transition of these flow regimes can be find out by flow regime map in the form of dimensionless particle size and liquid superficial velocity. The regime of conventional fluidization and fixed bed is determined by the min. fluidizing velocity (U_{mf}).

The prime objective of the current study is to predict the hydrodynamics of two phase liquid-solid fluidized bed using semolina particles as a bed material. The research was conducted by studying the variation of a key hydrodynamics factor "pressure drop" with liquid superficial velocity and effect of static bed height on "minimum fluidization velocity". Pressure drop and min. fluidizing velocity are the significant hydrodynamics factors that are used mainly for the determination of hydrodynamics behavior of the bed. Many researchers have determined the hydrodynamics behavior of a fluidized bed using different particles but there is no sufficient research data on the hydrodynamics behavior of fluidized bed using sticky particles, so this topic has been selected for the this research. We used semolina particles which are sticky particles and then we studied the hydrodynamics behavior for bed of semolina particles in liquid-solid fluidization. Now a days, fluidization is also employed for the waste water treatment. This technique uses the catalyst (in some cases activated carbon) which shows stickiness when they come in contact with water and therefore

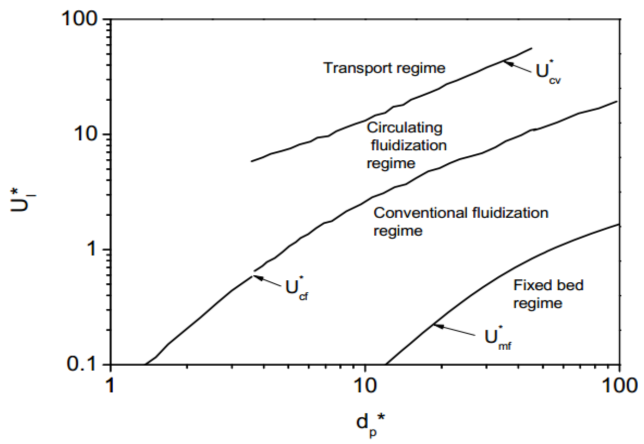

Figure 1: Flow Regime Map for liquid solid Fluidization.

it is necessary to determine the hydrodynamics of bed of such type of particles for development and scale up of the fluidization operation [18].

Experimental Setup and Method

The experimental set up consist of a transparent column which is made-up of acrylic with dimensions of 60 mm internal diameter with a maximum height of 1000 mm and a wall thickness of 2 mm. Liquid (water) enters into the column from bottom through distributor, distributor ensure the uniform flow of water into the column. Distributor has perforates in a pattern of triangular pitch. A pump of 0.5 hp is used to pump the water through the column. Rota meter is used to control the flow of liquid and three manometers are used to measure the pressure drop at different points across the bed. A reservoir tank is used to store the fluid. A known quantity of semolina particles was loaded through the provision in the column. The pump was started to fill the column with the liquid and then initial static bed height was noted. Then liquid (water) was allowed to pass through the column and the velocity of fluid was increased till the onset of fluidization. During this operation, the pressure drop was observed in manometers with the varying fluid flow rates. In the next experimental run, the static bed height was changed and same above stated procedure was repeated. Schematic diagram of the experimental set up is shown in Figure 2.

Three manometers are used for measuring the pressure drop at different points across the column, first manometer is inserted below the distributor plate to find the pressure of liquid (water in our case) before entering the bed of particles while the second manometer is inserted just above the distributor plate to find the pressure drop across distributor plate. Third manometer is inserted at the top the column to find the pressure drop across bed. We observed the values of second and third manometer for our work to find the pressure drop which is presented in Table 1.

Results and Discussion

Minimum fluidization velocity

Minimum fluidization velocity is the liquid superficial velocity at which bed of solid particles becomes incipiently fluidized and at this velocity the upward force (drag force) becomes equal to the downward force (weight of solids). Minimum fluidization velocity is a important parameter in the design of a fluidized bed reactor. The equation used for the determination of U_{mf} is the Ergun equation which is based on a

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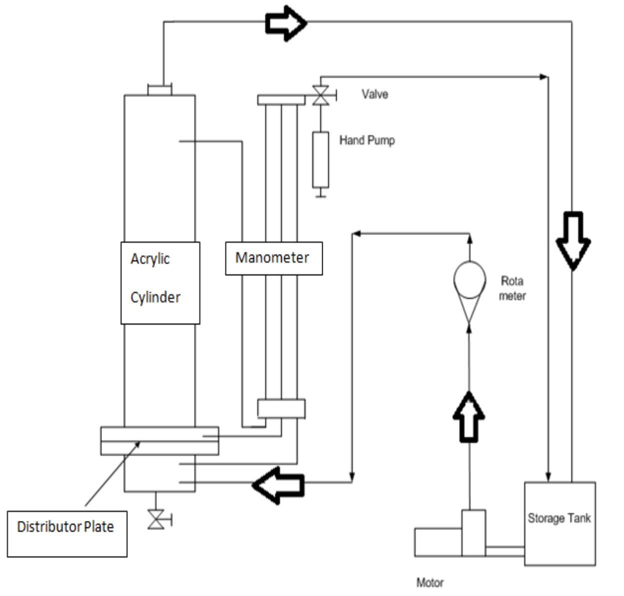

Figure 2: Schematic diagram of experimental set up.

Liquid Superficial Velocity	ΔP_2 (H=5.0cm)	ΔP_4 (H=6.0cm)	ΔP_6 (H=7.0cm)
m/sec	Pa	Pa	Pa
1.75×10^{-4}	1264.2	1940.4	2234.4
2.109×10^{-4}	2058	2067.8	2479.4
2.46×10^{-4}	2940	2508.8	2665.6
2.81×10^{-4}	3773	3165.4	3057.6
3.16×10^{-4}	4419.8	3792.6	3459.4
3.52×10^{-4}	4949	4312	3841.6
3.86×10^{-4}	5831	5272.4	4625.6
4.21×10^{-4}	6183.8	5654.6	5301.8
4.57×10^{-4}	6242.6	5664.4	5497.8
4.92×10^{-4}	6272	5684	5517.4
5.27×10^{-4}	6272	5684	5521.2

Table 1: Pressure Drop at different static bed Heights.

assumption that the drag force of the liquid flowing with a superficial velocity (U_{mf}) is equivalent to the weight of solid particles in the bed.

$$U_{mf} = \frac{d_p^{\,2}(\rho_s - \rho_\phi)}{150\mu f}\left(\frac{\epsilon_{mf}^{\,3}.\phi_s^2}{1-\epsilon_{mf}}\right) \qquad (1)$$

The minimum fluidization velocity in our case comes out to be 0.404 mm/sec. When initial static bed height was changed in the next experimental run, the U_{mf} was the same. Therefore we can say that minimum fluidization velocity does not depends on the initial static bed height, it depends on the size and density of the particles [15]. If the density of the particles are higher, then it requires greater upward forced to suspend/fluidize, this could be justifiable in a way that when particles are heavier (having density greater than the fluid) than the fluidizing fluid, then it is quite obvious that we have to provide greater upward force to overcome the gravitational forced to fluidize the particle. In our case (bed of semolina particles), the bed particles are heavier than the flowing liquid, i.e., water (density of semolina>density of water), therefore they are fluidized by the upward flow of fluid and due to their cohesiveness (since semolina particles are sticky particles) a greater upward drag force is required for fluidization. That is why value of U_{mf} comes out relatively higher in our case. Knowledge of minimum fluidizing velocity (U_{mf}) is used to evaluate the range of operating conditions and the energy requirement for a fluidized bed reactor.

Pressure drop profile

Pressure drop is the most important parameter used for the determination of hydrodynamics of a two-phase fluidized bed. Pressure drop is the key parameter which has a decisive role in the economical and efficient operation of a fluidized bed reactor. The Pressure drop is observed through manometers across the bed. These manometers provide the pressure drop in term of pressure head and then we converted it into Pascal. The observation data collected at different static bed heights is given in Table 1.

Pressure drop increases with the increase in liquid superficial velocity till the onset of fluidization, once fluidization is achieved, the pressure drop becomes constant. The same trend is shown in Figure 3a Semolina particles are the sticky particles and they offer more pressure drop than any other type of particles (sand etc.) due to their cohesiveness. Because when fluid is passed through the bed of semolina particles, they remain intact as a fixed bed, and hence more pressure is lost in making the sticky bed particles to fluidize. When bed is fluidized, the pressure drop becomes constant because the resistance the resistance for the fluid (liquid) decreases significantly. With the increase in the liquid superficial velocity, the bed voidage also increases due to the expansion of bed particles, this causes the pressure drop to increase till fluidization state reached. Figure 3b demonstrate the pressure drop variations for fluidization and de-fluidization i.e., pressure drop profile when liquid flow rate is increased from zero to U_{mf} and then pressure drop profile when liquid flow rate is decreased from U_{mf} to zero.

Conclusions

The minimum fluidization velocity (U_{mf}) was found independent of initial static bed height (solid loadings) and it depends on the particle density and particle diameter. U_{mf} is the key factor in the design and scale up of a fluidized bed reactor. Bed of particles remain fixed till the minimum fluidizing velocity is achieved. Pressure drop in case of bed of semolina particles is high due to the cohesiveness of the semolina particles. Pressure drop values are higher for the bed of semolina particles as presented in Figure 3a due the sticky nature of particles.

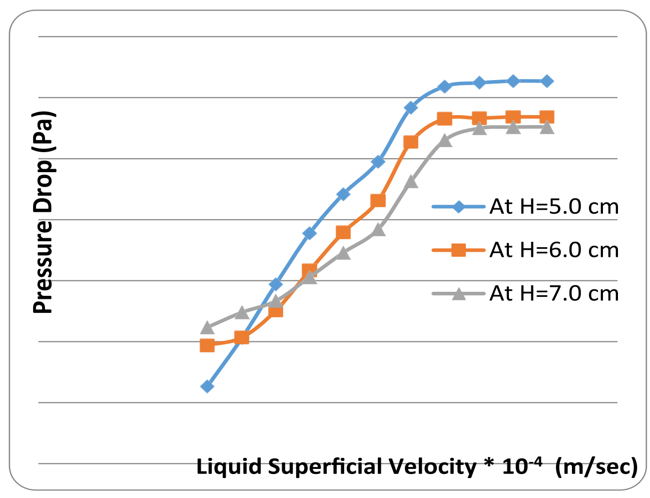

Figure 3a: Pressure Drop variations.

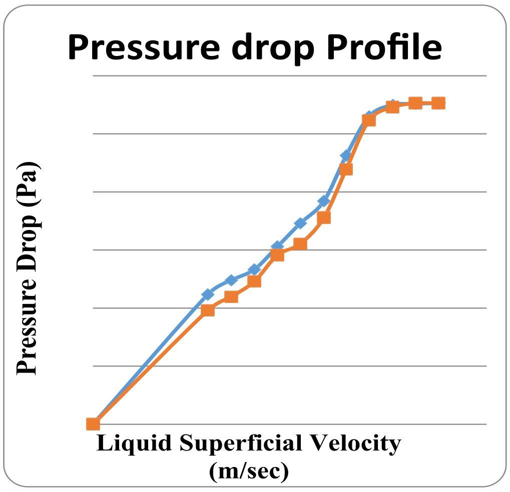

Figure 3b: Pressure Drop variations for the fluidization and de- fluidization.

Pressure drop increases till the minimum fluidization velocity is reached and then on further increase in liquid velocity above U_{mf}, pressure drop remains constant. Further increase in the liquid superficial velocity above the U_{mf} leads to particles vigorous motion, that is the main cause of turbulence and better mixing in the fluidization technique. Pressure drop is the important parameter in determination of hydrodynamics because it enables us to determine the energy losses and friction factor which are helpful in predicting the stable flow conditions necessary to efficiently operate the fluidized bed reactor for a given operation. Liquid-solid fluidized bed reactor are now widely used technique which is extensively used in the hydro metallurgy, waste water treatment and especially in bio-processing.

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