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INVESTIGATION OF THE DEPENDENCE OF PRESSURE DROP AND PARTICLES FLOW RATE ON THE PARTICLE DIAMETER IN SPOUT-FLUIDIZED BED

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Abstract: *The spouted and spout-fluidized bed systems have been designed to overcome the limitations of fluidized systems, particulary where there is a need to utilize large particles in the process. These beds have great significance and are applied for various processes in industry. They are formed by introducing fluid into a column with a packed bed, establishing the vertical transport of particles upwards through the center of the column. The entire packed bed in the annular area slides down as the particles are transported upwards from the bottom of the bed. Sometimes, a central pipe is installed in the axis of the spouted bed column, through which transport occurs, significantly reducing the pressure drop in column and increasing operational efficiency. The aim of the presented paper is the measurement of fluid flowrate, particle flowrate, and pressure drops in spout-fluidized bed with a central pipe, at a certain distance from the bottom of the bed. Glass particles were used for these measurements, and their characterization was performed initially. Fluid flow was varied in the annulus and central pipe, followed by measurements of pressure drops.*

Keywords: *fluidization, glass particles, pressure drop, spouted bed*

1. INTRODUCTION

The terms "fluidization" and "fluidized bed" were initially employed in the 1940s to describe the use of a fluidized bed for the drying of peas, lentils, and flax seeds. With the development of fluid catalytic cracking, a process for converting heavy hydrocarbons in petroleum refineries, fluidization became a mature process operation with a growing number of practical applications and occupies a significant place in the industry today. [1]

One of the most significant characteristics of a fluidized system is the effective mixing within the fluidized bed, enabling efficient heat transfer between solid particles and gas. It is primarily used for physical processes such as drying, mixing, granulation, cooling, and heating, but it is also utilized for chemical operation involving interactions between solids and gases. Such processes are fast, achieve excellent homogeneity, and offer the possibility of continuous operation in devices for continuous production. [2]

The properties of a fluidized bed depend on the type of material, particle size, shape and qualities. The behavior of one material during fluidization cannot be extrapolated to the behavior of another material. [3]

Pressure drop in a fluidized bed is given by Eq. (1):

$$-\frac{\Delta P}{H} = \left(\rho_p - \rho_f\right) g \left(1 - \varepsilon\right) \tag{1}$$

where: *(ΔP)*- the pressure drop in the bed; *H*- the column height; *g*- the gravity constant; ρ_p – the density of the bed; ρ_f – the density of the fluid; *ε*- the porosity of the bed [4]

Fluidization is a well-studied concept. It occurs when the frictional force between the fluid and particles becomes equal to the effective weight of the bed per unit surface area of the column. In that moment, particles redistribute, causing the bed to expand, while its porosity increases. As fluid velocity increases the distance between particles expands, leading to an increase in porosity. However, the pressure drop remains constant. The fundamental fluidization equation states that the pressure gradient in the bed is proportional to the particle concentration. [4]

Research has shown that in multiphase flow systems, two-phase moving fluid-particles beds occur in forms such as packed bed, spouted bed, spout-fluidized bed, spout-fluidized bed with a central pipe and spout-fluidized bed with a central pipe and conical base. These systems can be implemented within a cylindrical column by installing a nozzle at its flat or conical base and using an annular fluid distributor. [4,5]

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The spouted bed represents a moving bed of particles that occurs in such fluid flow through a nozzle, providing vertical particle transport upwards in the form of a fountain. Consequently, particle movement downwards occurs in the annular space, forming a packed bed. In addition to the described particle movements, there is also their radial movement from the annular part to the central part of the bed (fountain), most pronounced at the top of the bed. At the top of the fountain, particles lose kinetic energy and fall onto the top of the annular space. The primary benefit of this system is the possibility of gas-particle contact for particles that cannot be fluidized. [6]

The estabilishment of the fountain bed is illustrated in Figure 1, where (a) presents a packed bed with particles in a quiescent state. Subsequently, with the introduction of fluid into the system, the fountain bed forms at the point of minimal fluidization velocity (b). As the fluid flow rate increases, a more pronounced fountain forms, as shown in Figure 1 (c). Following this stage, the bed transforms and becomes filled with large bubbles. (d) [7]

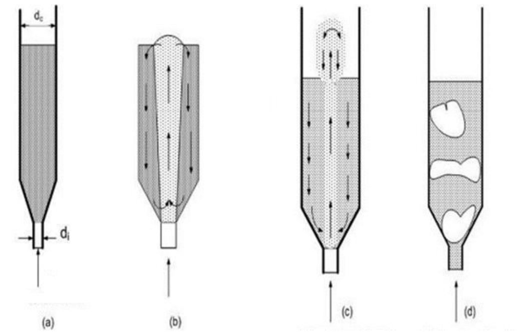

Figure 1. Estabilishment of the fountain bed [7]

The spout-fluidized bed is formed by simultaneously introducing fluid into the particle bed through a nozzle and an annular distributor. This allows for the combination of spout bed characteristics with those of the spout-fluidized bed, with the latter exhibiting significantly lower pressure drop compared to the spouted bed. [8] In comparison to the spouted bed, better gas-particle contact and better mixing within the annulus are facilitated. [7]

Some deficiencies of the spout and spout-fluidized beds have led to their development, resulting in the draft-tube insert placed within the bed axis at a certain distance from the nozzle or column base. The utilization of such a draft-tube insert enables a reduction in pressure drop within the bed. Such a bed is physically divided into two zones: vertical particle transport within the draft-tube and moving packed/fluidized bed particles within the annular space (Fig. 2.).

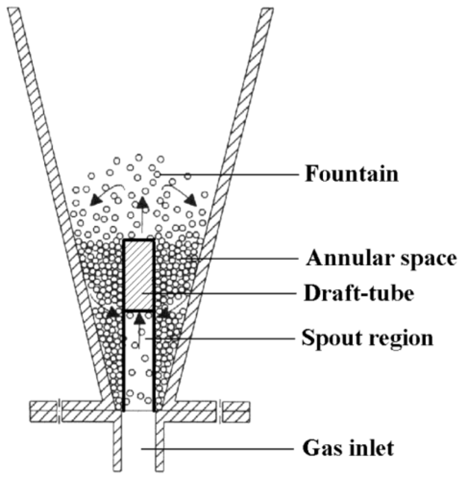

Figure 2. Spout-fluidized bed with a central pipe [4**]**

The aim of this paper is to experimentally investigate the pressure gradient and particle flow rate through a modified spout-fluidized bed with a draft tube, using spherical glass particles.

2. EXPERIMENTAL DETAILS

The apparatus used in the experiment consists of: a fluidization column with a central pipe and a bypass, six sensors measuring pressure in the central pipe, and three sensors measuring pressure in the annulus, at a known height from the bottom of the column, valves, two rotameters, a compressor, and a blower. Air was used for fluidization, with the blower providing air flow through the annulus, while the compressor provided air flow through the draft-tube. Rotameters were used to determine the required air flow necessary for the experiment: one rotameter measured the air flow through the pipe and the other measured the flow through the annulus. Valves were used to adjust the air flow through the pipe. The fluidization column is shown in Figure 3.

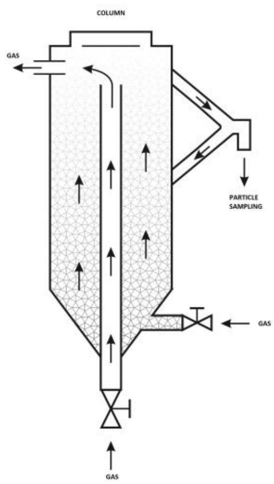

Figure 3. Schematic representation of the fluidization column

The column contains particles, and experiments were conducted using glass particles, referred to as Glass Particles 1. Using the bypass, the particles circulate and return to the column, with a portion of the particles being captured in a collection vessel. The mass of the captured particles is measured over a precisely defined time interval.

2.1. Characterization of particles

The appearance of Glass Particles 1 used in the experiments is shown in Figure 4. The total mass of glass particles used was 5790g.

Figure 4. The appearance of Glass Particles 1

Determining the average particle diameter

Before the experiments began, the particles were characterized by measuring their diameter and density. The diameter was determined by measuring 50 randomly selected glass particles using a digital micrometer. For each particle, the diameter was measured, and based on the number of samples taken, the average particle diameter was calculated.

$$ds = \frac{\sum di}{n} \qquad (2)$$

Where ds is the calculated average diameter, Σdi is the sum of all measured diameters, and n is the number of measured diameters. The obtained average particle diameter was 1.07mm.

Determining the density of particles

The density of the particles was measured using a pycnometer. Using a digital scale, the mass of the empty pycnometer (m_{pik}), the mass of the pycnometer with particles (m_{pikc}), the mass of the pycnometer with water (m_{pikv}), and the mass of the pycnometer with particles and water ($m_{pikc,v}$) were measured. Based on the known formula for determining density and the obtained masses, the density of the particles was calculated. The density of the glass particles used in the experiments was 2796 kg/m^3.

$$\rho = \frac{\left(m_{pikc} - m_{pikv}\right)}{\left(\left(m_{pikc} - m_{pik}\right) + m_{pikv}\right) - m_{pikc,v}} \qquad (3)$$

2.2. Experiments in spout-fluidized bed

In the described experimental setup, 81 measurements were taken with Glass Particles 1. During each experiment, the air flow rate through the central pipe and the air flow rate through the annulus were varied. The air flow rate through the central pipe for Glass Particles 1 ranged from 160 to 260 l/min. The air flow rate through the annulus for Glass Particles 1 was varied from 8 to 12 m^3/h. The maximum air flow rate through the central pipe for Glass Particles 1 was limited to 260 l/min because pressure sensors exceeded their range at higher flow rates, making such measurements impractical. The lower limit of the range where measurements were conducted represents the minimum flow rate at which a spout-fluidized bed is established in the tested system. The conditions of the experiment are shown in Table 1.

For each experiment, both air flow rates through the central pipe and the annulus were set. A known mass of glass particles, measured before the experiment began, was introduced into the fluidization column, which was then sealed. Airflow was subsequently enabled. At a specified airflow rate, the time taken for the particles to exit the system via the bypass, once it was opened, was measured. The particles were collected in a collection vessel, their mass was measured, and then they were reintroduced into the column to continue the experiment.

Table 1. Conditions of the experiment

type of particles	flow through	
	annulus, m^3/h	central pipe, l/min
Glass Particles 1		160
		210
		170
	8	220
	9	180
	10	230
	11	190
	12	240
		200
		250
		260

3. RESULTS AND DISCUSION

For glass particles 1, the pressure profiles through the central pipe and the annulus were determined, as well as the impact of fluid flow rate in the central pipe and in the annulus on the pressure gradient. Based on the measured mass of particles at different fluid flows through the central pipe and annulus, the particle flows and the dependence of particle flow on fluid flow were determined. All the obtained results are graphically presented in the continuation of the paper.

3.1. PRESSURE PROFILE

For glass particles, the pressure profile in the system along the height of the column in the central pipe and in the annulus is shown. The results of experimental measurements are that higher fluid flows through the system will result in higher pressure.

The pressure profile along the central pipe

The pressure profile in the central pipe is shown in Figures 5 and 6. The sensors were positioned to measure the pressure at a point relative to atmospheric pressure. The minimum flows in the central pipe and in the annulus at which a spouted-fluidized bed is formed for glass particles 1 are 160 l/min and 8 m³/h.

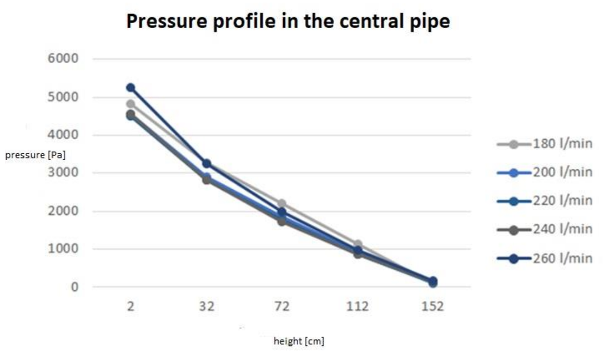

Figure 5. The pressure profile along the central pipe for different flows through the pipe for Glass Particles 1 at constant flow in the annulus of 8 m³/h

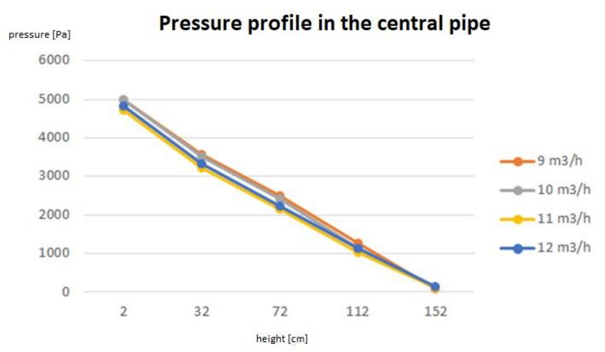

Figure 6. The pressure profile along the central pipe for different flows through the anulus for Glass Particles 1 at constant flow in the central pipe of 160 l/min.

Figures 5 and 6 illustrate the pressure profile along the central pipe for Glass Particles 1. The x-axis represents the height where sensors were positioned to measure pressure, with their values shown on the y-axis. The sensors are located within the central pipe. From these figures, it can be concluded that increasing the fluid flow through both the central pipe and the annulus leads to an increase in pressure within the system. Additionally, a clear observation is the descrease of the pressure from bottom to top of the column (with the highest messure at the bottom). The results obtained for the lowest flow rate through the central pipe of 160 l/min at constant flow rate through the annulus of 8 m³/h were not considered valid because the bed remained unstable throughout the experiment. Similar considerations apply to the results obtained for the flow rate through the annulus of 8 m³/h at constant flow rate through the central pipe of 160 l/min.

3.2. THE INFLUENCE OF FLUID FLOW ON PRESSURE GRADIENT

For each experimental pressure measurement in the central pipe and annulus, the pressure gradient was determined at characteristic points. The dependence of the pressure gradient in the central pipe on the flow rate in the central pipe was established, assuming constant flow in the annulus. Similarly, the dependence of the pressure gradient in the central pipe on the flow rate in the annulus was determined, assuming constant flow in the central pipe. Results were obtained and graphically presented for glass particles. The x-axis shows fluid flow values, and the y-axis shows pressure drop.

The influence of flow on the pressure gradient in the central pipe

Figures 7 and 8 illustrate the impact of flow rate on the pressure gradient in the central pipe for Glass Particles 1. In Figure 7, the pressure gradient in the central pipe (y-axis) is plotted against the fluid flow rate in the annulus (x-axis), varied from 8 to 12 m³/h, with flow rates through the central pipe ranging from 160 to 260 l/min.

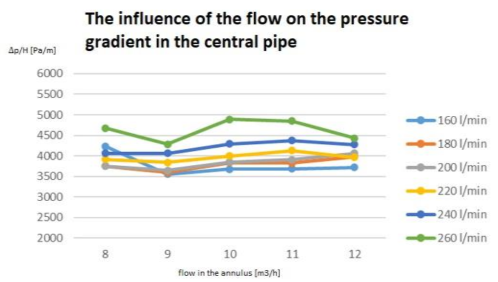

Figure 7. Pressure gradient in the central pipe as a function of fluid flow in the annulus for different flows through the pipe for Glass Particles 1

Figure 8 shows the pressure gradient in the central pipe (x-axis) plotted against the fluid flow rate through the central pipe (y-axis), varied from 160 to 260 l/min, with flow rates through the annulus ranging from 9 to 12 m³/h. According to the expected trend, increasing the fluid flow leads to a greater pressure drop in the central pipe.

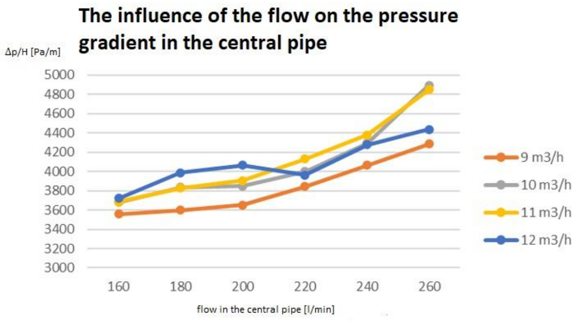

Figure 8. Dependence of the pressure gradient in the central pipe on the fluid flow through the central pipe for different flows through the anulus for Glass Particles 1

The influence of fluid flow on the pressure gradient in the annulus

Figure 9 shows the influence of flow on the pressure gradient in the annulus, with fluid flow through the annulus (x-axis) varied from 8 to 12 m³/h, while fluid flow through the central pipe (y-axis) varied from 160 to 260 l/min. From this figure, it can be concluded that increasing the fluid flow through both the central pipe and the annulus leads to an increase in the pressure gradient in the annulus. Additionally, it can be observed that the flow rate through the annulus has a greater impact on the pressure gradient in the annulus compared to the flow rate through the central pipe.

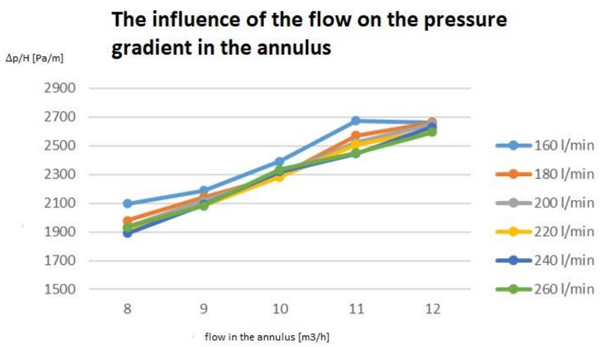

Figure 9. Pressure gradient in the annulus as a function of fluid flow in the annulus for different flows through the pipe for Glass Particles 1

3.3 THE INFLUENCE OF FLUID FLOW ON PARTICLE FLOW

For each experimental fluid flow measurement, the mass flow of the particles through the system was determined. Using the mass of particles, the mass flow rate and volumetric flow rate of particles of known density, previously determined in the system, were calculated. Fluid flows in both the annulus and central pipe were varied to establish the dependency of particle flow rates on fluid flow rates, which is further detailed in the study.

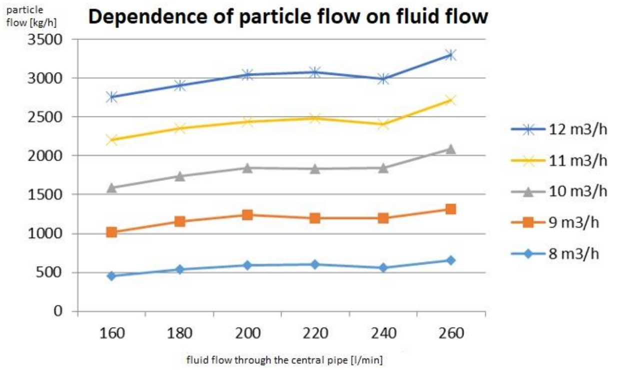

Figure 10. Dependence of particle flow on fluid flow through the central pipe for different flows through the anulus for Glass Particle 1

It can be seen that increasing the fluid flow through both the central pipe and the annulus results in an increase in the flow of Glass Particle 1 through the system. The increase is approximately linear.

4. CONCLUSIONS

From the obtained results of the pressure profiles along the central pipe for Glass 1, it can be concluded that the minimum flows at which a spouted-fluidized bed forms are 160 l/min through the central pipe and 8 m³/h through the annulus. The lowest pressure in the spouted-fluidized system containing Glass Particles 1 is at the top of the column. Increasing the fluid flow through both the central pipe and the annulus leads to an increase in pressure within the system.

The influence of flow on the pressure gradient in the central pipe for Glass 1 can be determined with minimum flows of 8 m³/h through the annulus and 160 l/min through the central pipe. Flows were varied up to 12 m³/h and 260 l/min. Increasing the fluid flow results in a greater pressure drop in the central pipe. Additionally, increasing the fluid flow through both the central pipe and the annulus leads to an increase in the pressure gradient in the annulus. The flow rate through the annulus has a greater impact on the pressure gradient in the annulus than the flow rate through the central pipe.

Experimental profiles and pressure drops were investigated in a spouted-fluidized bed with a draft tube, using glass particles for the experiments. Pressure profiles along the central pipe and the annulus, pressure gradients in the central pipe and the annulus, as well as particle circulation flows within the system, were determined.

The conclusion drawn from the analysis of the results is that higher fluid flows through both the central pipe and the annulus lead to higher pressure within the spout-fluidized bed. Increasing both flows results in an increase in the pressure gradient. As for pressure drops, they also increase with higher fluid flows.. Based on the results, it was also determined that increasing the gas flow rate through the central pipe and the annulus leads to increased particle flow through the system.

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