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Effect of Horizontal Passage Length on Solid Recycle Through a Loop Seal in a Circulating Fluidized Bed

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EFFECT OF HORIZONTAL PASSAGE LENGTH ON SOLID RECYCLE THROUGH A LOOP SEAL IN A CIRCULATING FLUIDIZED BED

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ABSTRACT

Solid flow through the loop seal of a circulating fluidized bed (CFB) was studied by investigating the effect of the horizontal passage length on solid flow through the loop seal. As horizontal passage length increased it was found that the minimum aeration required also increased. As well the maximum obtainable solid flux decreased with increasing passage length due to the increased resistance in the longer passage. The increased resistance to solid flow through the passage was also seen in the increasing pressure drop per unit length across the passage, as the passage length increased. The division of air flow through the loop seal was also investigated in order to determine how the solids were driven through the loop seal. At high solid flow rates all of the supply chamber aeration flowed into the horizontal passage along with an amount of air entrained by the solids falling down the standpipe.

INTRODUCTION

Circulating fluidized beds (CFB) are in wide use in gas-solid contacting processes such as catalytic cracking, combustion and gasification of solid fuels. In a CFB the recycle rate of the inert bed solids around the loop is controlled by a valve at the bottom of the standpipe, which is generally non-mechanical.

Non-mechanical valves employ no moving mechanical devices, but control the flow of solids through aeration and maintain the required pressure drop across the valve using the weight of the solids in the standpipe. The most common of these non-mechanical valves is the loop seal. Although in wide use in many commercial processes, a limited amount of research is available on the operation of these devices (1).

The loop seal is divided up into a supply chamber and a recycle chamber, the two connected by a horizontal section or "passage". The supply chamber forms the bottom of the cyclone's standpipe, and the recycle chamber is connected to the lower section of the CFB by means of the recycle pipe.

The flow of solids into the supply chamber is considered to be a moving packed bed flow, (2). It is usually provided with aeration to decrease the inter-particle friction forces, aiding the movement of solids. The aeration in the supply chamber should not exceed the minimum fluidization velocity of the solids in the standpipe, because at velocities above U_{mf} the seal is lost and solids and gases will flow from the riser up through the standpipe. Namkung et al. (3) found, using Geldart group D particles, that solid circulation was greatest when fluid velocity in the supply chamber was between 0.9-1.1 U_{mf}. The solids in the recycle chamber are however kept in a bubbling fluidized state causing the bed to expand, flow over a weir into the recycle pipe and back into the riser. As the aeration to the recycle chamber increases bubbles will form further expanding the bed over the top of the weir, (4)

Several studies (2), (3) reported data on loop seals with negligible distance between the supply and recycle chamber. These works do not take into account an important physical feature of commercial loop seals that is characterized by a finite distance between the walls of the supply and recycle chamber. This finite distant is governed by the thickness of insulation and refractory required to be put on the walls of the un-cooled loop seal. It was not known previous to this study whether this finite horizontal length has any influence on the solid flow rate between the two chambers.

EXPERIMENTAL

Experiments were conducted using a cold (room temperature) CFB consisting of a riser, three gas/solid separators (a cyclone, u-beam separator and bag house) in series, a standpipe connected to a butterfly valve and a loop seal. The riser is made of Plexiglas, has an internal diameter of 0.152 m and height of 5.181 m.

The recycle system consists of a standpipe with a rectangular (0.071 m x 0.080 m) cross section and 3.355 m in height, connected to a loop seal. The supply and recycle chambers are connected by a horizontal section of length L_s, that could be varied easily. Equal amounts of air were fed into the supply and recycle chambers of the loop seal, with no aeration in the horizontal passage. The air velocity in the riser was kept constant at 5.86 m/s as the loop seal aeration was varied between 0 – 0.0063 m^3/s. Air flow rate in the riser was measured using a duct-type flow meter. For the loop seal three rotameters were used; one measuring and controlling the total flow rate feeding the two others which measured the flow to each chamber.

The solid inventory was held constant by maintaining the same height of solids in the standpipe. A silica sand of mean particle diameter of 171μm and particle density of 2856.85 kg/m^3 was used. The minimum fluidization velocity, U_{mf} for this bed solid was found to be 0.109 m/s.

Solid flow rate was measured by closing a butterfly valve at the top of the standpipe and measuring the time it took for the solids to fill a known volume. Mass flux was calculated using the measured bulk density of the solids and was measured against the cross-sectional area of the riser.

Pressure taps were located in the standpipe at a height of 0.2159m, in the supply and recycle chambers (at a height of 0.0254 m) and at the start and end of the horizontal passage at a height of 0.0254 m (Figure 1a). The taps were connected to pressure transducers and the signals were processed and recorded using a data acquisition system.

The relative velocity of the gas, with respect to the solids, through the supply chamber and the standpipe was found using the pressure drop across a section of the standpipe. The Ergun equation (2), (5) gives the pressure drop ΔP_s across a bed with gas-solid slip velocity Δu (Equation 1).

$$\frac{\Delta P_S}{L_S} = 150\frac{(1-\varepsilon_m)^2}{\varepsilon_m^3}\frac{\mu_g \Delta u}{(\Phi_s d_p)^2} + 1.75\frac{(1-\varepsilon_m)}{\varepsilon_m^3}\frac{\rho_g \Delta u^2}{(\Phi_s d_p)} \tag{1}$$

The gas-solid slip velocity, Δu is the sum of upward gas velocity u_{sg} and downward solid velocity u_{ss}.

$$\Delta u = u_{sg} + u_{ss} = \frac{U_V}{\varepsilon_m} + \frac{G_s}{\rho_p(1-\varepsilon_m)} \tag{2}$$

The gas velocity in the standpipe (U_V) is found by subtracting the velocity of the solids, u_{ss} flowing through the standpipe from the calculated relative velocity (Eqn. 2); giving a positive upward flowing gas or negative downward flow of gas. The gas flow rate though the horizontal passage is found by subtracting the gas flow into the standpipe from the total gas flow entering the bottom of the supply chamber, gas velocity through the horizontal passage (U_H) is then found.

A separate experiment was conducted to measure the angle of repose of various particles as it relates to the flow through the horizontal passage (Figure 1b).

Bulk solids of uniform grain size, free from surface moisture are rated free-flowing (6). If free-flowing bulk solids are discharged through a vertical or horizontal opening the angle formed by the free surface of the grain to the horizontal plane is called the angle of repose (Figure 1b). The angle of repose varies, depending on the particle size and the shape of the individual particles (6).

In this experiment, air was supplied gradually to the supply chamber as indicated in Figure 1b. The horizontal length of the sand spread was recorded at different air velocities to calculate the angle of repose for the known vertical height of the sand heap. Since the magnitude of the inter-particle frictional forces and therefore the angle of repose depend on the shape and size of particles, four different types of particles were used: spherical glass beads with mean diameters of 124.3 μm and 644.6 μm and silica particles with mean diameters of 92.2 μm and 183.9 μm (Table 1).

RESULTS AND DISCUSSION

Effect of inter-particle friction

The angle of repose or angle of friction of a particle is a measure of the inter-particle friction. As aeration into a bed of solids increases the inter-particle friction decreases, the angle of repose of the solids decreases and the solids 'spread out' more (Figure 2). If this angle of repose is small enough and the horizontal passage length short enough, then solids will flow into the recycle chamber without the need for any supply chamber aeration as in the case of a slit opening. If the horizontal passage length is long then the bed must be aerated and inter-particle friction decreased to the extent that the resulting angle of repose is below that created by joining the top edge of the supply chamber to the bottom edge of the horizontal section (β in Figure 1b). As the horizontal passage length increases further, the angle β decreases and the resulting angle of repose (α) needs to drop below this value using higher aeration rates. If the velocity exceeds U_{mf} of the particles then α becomes zero and the solids behave like a liquid and flow over to the recycle chamber. At velocities greater than U_{mf} the solids in the horizontal passage will then be conveyed by both the static pressure from the solids in the supply chamber as well as the drag force from the supply chamber aeration.

It can be seen that the initial angle of repose for the two types of glass bead is less than the two different silica sand particles (Figure 2). This is because the sphericity of the glass beads is larger than the silica sands (Table 1), creating less inter-particle friction making them more mobile. On the other hand, the velocity at which the coarse glass beads becomes horizontal and starts flowing is higher than the other two particles, because of their larger size and consequent higher minimum fluidizing velocity (U_{mf}) (Table 1).

Effect of aeration and horizontal passage length on solid flow

The solid flow rate was measured for a number of different loop seal aeration rates (U_H/U_{mf}). The finite length of the horizontal section offered resistance to the solid flow, thus the air flow through the horizontal passage must exceed a threshold before solid flow is initiated (2), (5) (Figure 3).It is also noted that the rate of change of solid flow increases as the horizontal passage length increases.

Results of three different passage lengths are shown in Figure 3; although data for very low solid flow rates is not available, one can easily infer from the plot that solid flow only occurred for horizontal velocities (U_H) through the passage well in excess of U_{mf}. As can be seen in Figure 2, the angle of repose doesn't change significantly until the minimum fluidization velocity has been reached; therefore, an aeration rate equivalent to (U_{mf}*A_H) is necessary to overcome the inter-particle friction and allow the solids to flow into the recycle chamber.

It may be noted that by passing air through the horizontal passage in a quantity in excess of (U_{mf}*A_H) the particles are not necessarily rendered fully mobile as one would expect in a vertical column. Horizontal gas flow reduces the inter-particle friction which prevents particles subjected to vertical force, from moving horizontally. Figure 2 illustrates this point by showing how the angle of repose reduces with increasing air flow.

Also in Figure 3 it is seen that the solid flow rate increases with aeration rate, but levels off beyond a certain value, also shown by Basu et al. (2) and Kim et al. (7). This suggests that air flow through the horizontal passage can reduce the resistance through the loop seal only up to a maximum when the particles are rendered fully mobile. Beyond this additional air just flows through the horizontal passage without affecting the solid flow.

The aeration rate did not have any direct influence on the maximum flow rate, but the passage length did. The maximum solid flow rate is governed by the total resistance in the recycle circuit, wherein friction in the horizontal passage is just one component. Thus an increase in the horizontal length would not necessarily decrease the flow rate by the same amount.

Effect of passage length on pressure drop across the passage

When horizontal passage length is increased the pressure drop through the section increases due to the higher resistance in it. Figure 4 plots the pressure drop per unit length of fluidized solids in the passage against its non-dimensional length (*L/H*) for three different passage lengths.

When the horizontal gas velocity exceeds U_{mf}, the entire bulk of solids in the passage may not be rendered fully mobile leaving an area of stationary solids near the end of the horizontal passage. As the horizontal passage is increased this void increases, increasing the pressure drop and restricting the flow of solids.

The division of flow through the loop seal

Gas fed through the bottom of the supply chamber (Figure 1a) or into a vertical aeration section above the supply chamber does not flow entirely into the standpipe (5). A part of it flows into the recycle chamber through the horizontal section while the rest may flow into the standpipe. For low solid flow rates a small amount of air flows up the standpipe helping to 'lubricate' the solids in the standpipe (Figure 5). The remaining air flows through the horizontal passage at a horizontal velocity (U_H). The gas flow through the standpipe remained well below U_{mf} and no bubbling, indicative of local fluidization, was observed.

As the loop seal aeration is increased, the mass flux of solids around the CFB increases (Figure 3), causing a large amount of air in the standpipe to be entrained into the supply chamber. This causes a decreasing and eventual reversal of the air flow through the supply chamber, so that air flows downward (negative U_V). When this flow reversal occurs in the standpipe, the standpipe air combines with the supply chamber aeration and flows through the horizontal passage where air flow increases nearly linearly with the total loop seal aeration rate. For this reason one notices that the air velocity through the passage increases more rapidly when a flow reversal takes place in the standpipe.

CONCLUSIONS

1. The solid flow starts only after the airflow through the horizontal passage exceeds a threshold limit that increases with the horizontal passage length. The threshold is a result of the effect of aeration rate on the inter-particle friction forces.
2. Longer horizontal passage length offers greater resistance to solid flow and therefore conveys a smaller amount of solids at a given gas flow through this passage.

3. As horizontal passage length is increased the maximum obtainable solid circulation rate decreases due to the increased resistance in the horizontal passage.
4. As horizontal passage length is increased the pressure drop across the passage increases, due to the constricting of the passage by the increasing zone of stationary solids at the end of the horizontal passage.
5. Aeration into the supply chamber is split such that the velocity of air in the supply chamber or the stand pipe remains below minimum fluidization with the remaining flow conveying solids through the horizontal passage.
6. At high mass fluxes the entire supply chamber aeration flows into the horizontal passage along with air entrained by the solids.

NOTATION

A_H	vertical cross section area of the horizontal passage, m^2
d_p	mean diameter of be solids, m
G_s	solid flux around CFB loop, kg/m^2s
H	height of horizontal passage length, m
L, L_s	length of horizontal passage
ΔP_s	pressure drop across standpipe
Δu	gas-solid sip velocity
U_H	velocity of gas through horizontal passage
$U_{H,rel}$	velocity of gas through horizontal passage relative to solids
U_{mf}	minimum fluidization velocity of solids
u_{sg}, U_V	velocity of gas in the standpipe
u_{ss}	velocity of solids in the standpipe
α	angle of repose/friction of static bed of solids
β	angle of bed of solids
ε	voidage of bed in the standpipe
μ_g	kinematic viscosity of fluidizing gas
Φ_s	sphericity of particle
ρ_g	density of fluidizing gas

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TABLES AND FIGURES

Table 1: Properties of particles used in angle of repose experiment

Particle Type	Fine Glass Beads	Fine Sand	Medium Coarse Sand	Coarse Glass Beads
Mean Diameter (μm)	124.3	92.2	183.9	644.6
Initial Angle of Repose (deg)	24.0	33.9	33.3	26.0
U_{mf} (m/s)	0.0170	0.0155	0.0340	0.3354
Sphericity	0.8894	0.7918	0.7804	0.8446

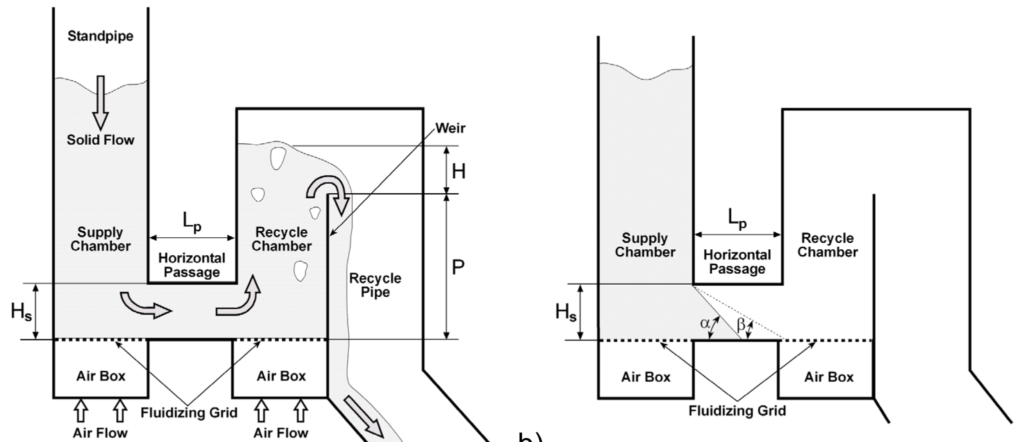

Figure 1: a) Loop seal set-up with finite passage length as used in current work. b) Angle of repose of sand and angle of sand required before sand can be recycled

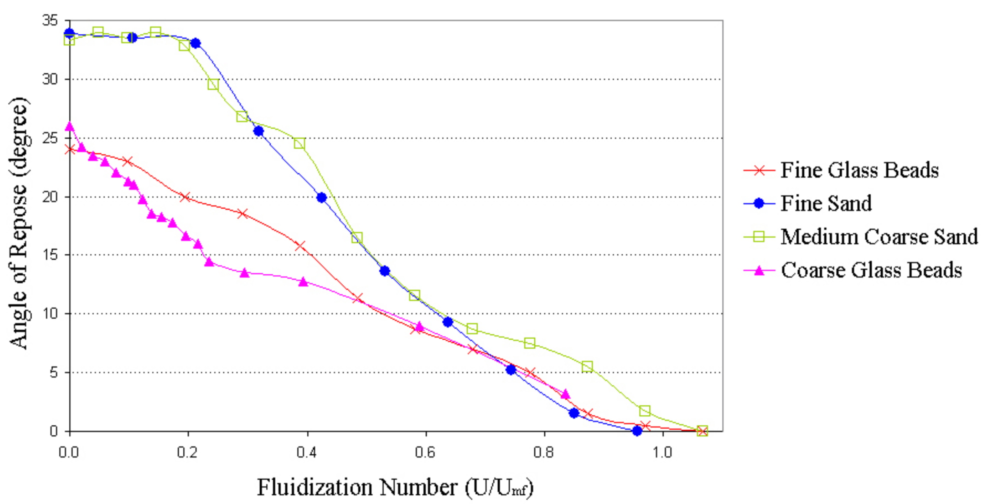

Figure 2: Variation in angle of repose/friction against aeration velocity with different particles

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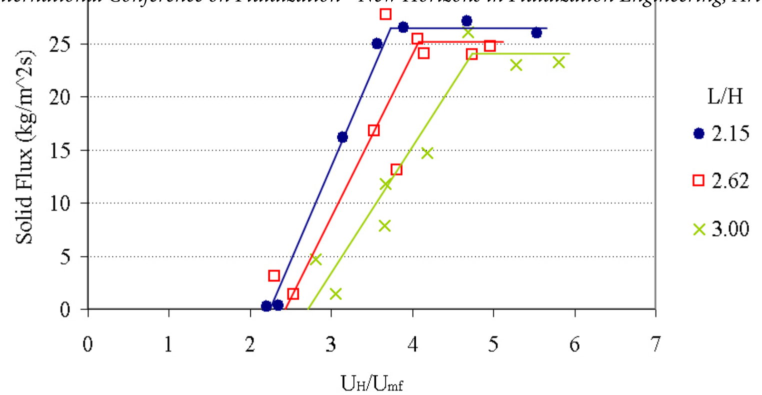

Figure 3: Changing Solid Flux with Supply Chamber Aeration and Horizontal Passage Length

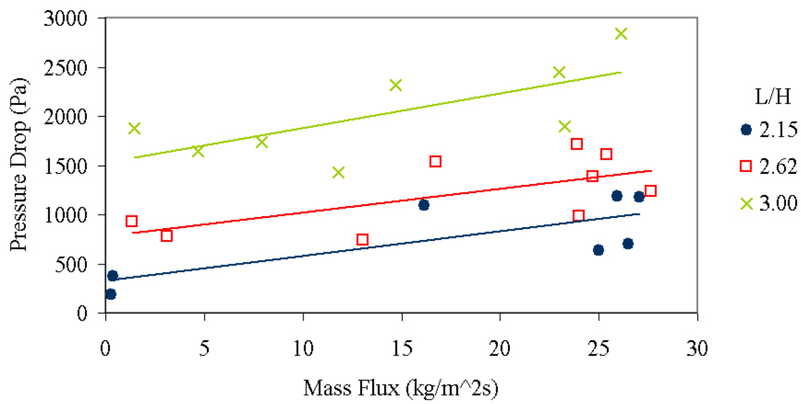

Figure 4: Pressure drop across the horizontal passage increases with solid mass flux and passage length.

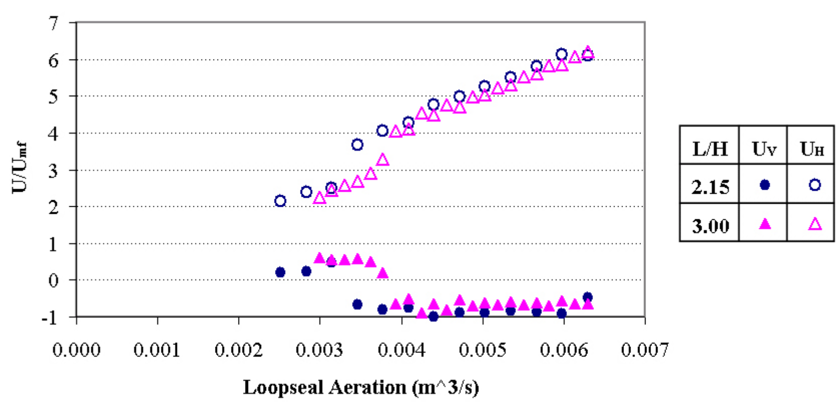

Figure 5: Split of aeration velocity (U/U_{mf}) between supply chamber and horizontal passage. Here U_V is the velocity of gas flowing up through the standpipe and U_H is the velocity of gas passing through the horizontal passage.