MASTER

VOID-GAS STRIPPING IN STANDPIPES

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ABSTRACT

A model of a packed-bed void-gas stripping section in a standpipe has been developed. This relative-velocity model allows the determination of the best stripper design for a particular application. This model was developed from the results of a void-gas stripping study using a nitrogen/oxygen gas system. The effects of stripping gas injection, particle size, particle density, stripper diameter, and solids flow rate on the amount of gas needed to strip were investigated. An example of how to design a packed-bed stripper is also presented.

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INTRODUCTION

During the transfer of solids from one fluidized bed to another via a standpipe, a substantial amount of gas can be transferred with the solids in the interstices. For safety reasons or to prevent contamination or dilution of product gas, it is frequently desired to prevent gas being transferred via a standpipe (from an upper fluidized bed to a lower fluidized bed) from coming into contact with the gas in the bottom bed. To accomplish this, a neutral or non-contaminating gas is usually added to the standpipe to replace, or "strip," the normal downcomer gas in the void spaces between the solids.

In coal conversion systems, steam is usually used as the stripping gas. Stripping is used in both the BI-GAS® and COGAS processes. For example, in the BI-GAS process it is used to strip product carrying gas from the feed line to the reactor.

Standpipes are usually operated in one of two modes: The fluidized-bed mode or the packed-bed mode. However, essentially no information exists in the literature on stripping in either standpipe flow mode.

Because of solids and gas backmixing in fluidized beds, it was thought that the packed-bed regime might be the mode in which interstitial standpipe gas could be stripped most efficiently. Therefore, the purposes of this study were to -

1. Determine the mechanism of stripping in a packed-bed standpipe.
2. Determine the effect of several system parameters on stripping requirements.
3. Develop a model to predict the minimum amount of stripping gas required for a particular application.

EQUIPMENT AND MATERIALS

A flow sheet of the equipment used in the investigation is shown in Figure 1. Solids were charged to the solids receiver at the top of the unit. They flowed out of the solids receiver through a 3-inch (7.6 cm) diameter pipe into an 18-inch (0.46 m) diameter bed fluidized with air. The solids then flowed out of the bed into the stripping test-section standpipe. Nitrogen stripping gas was added to the standpipe at the bottom of the stripping section. The solids flowed out of the stripping test section to the L-valve located at the bottom of the unit. The solids flow rate through the equipment was controlled by the rate at which air was supplied to the L-valve. The solids from the L-valve were metered into a 3-inch (7.6 cm) diameter

conveying line, in which air was used as the conveying medium. The solids were conveyed back up into the solids receiver at the top of the unit, thus completing the cycle. The conveying air was routed through three cyclones and two filters and then vented to the atmosphere.

The two different standpipe configurations used in the investigation are shown in Figure 2. The first standpipe configuration used had an interchangeable Plexiglas stripping section 7.25 feet (2.2 m) long at the top of the standpipe. Three different stripper diameters were used in this configuration: 4 inch (10.2 cm), 6 inch (15.2 cm), and 8 inch (20.3 cm). The solids from the stripping section passed through a concentric pipe reducer into a short 3-inch (7.6 cm) section and then into a 6-inch (15.2 cm) Plexiglas section. The solids then passed into a long 3-inch (7.6 cm) diameter standpipe section that led to the L-valve at the bottom of the unit.

The second standpipe configuration consisted of a 4-inch (10.2 cm) diameter clear PVC standpipe the entire length from the bottom of the fluidized bed to the L-valve.

The stripping gas was added to the standpipe in two different ways. For tests with nonporous particles, the stripping gas was added through four nozzles equally spaced around the circumference of the pipe. For the porous particle tests, the stripping gas was added through the four circumferential nozzles and a nozzle located at the middle of the standpipe.

Three oxygen analyzers were used to determine the percentage of oxygen in the standpipe. Two analyzers were located above the stripping gas injection point, and one was located below it. The locations of the analyzer sensors varied for each standpipe configuration and each stripper diameter used. The relative locations of the analyzer sensors for the two standpipe configurations tested are shown in Figures 3 and 4 and labeled x, y, and z. The actual locations of the sensors for the runs reported in this paper are listed in Table 1.

Five different materials were used in the study; the physical characteristics of each of these materials are given in Table 2.

PROCEDURE

In a typical run, the air flow rate to the fluidized bed and the solids conveying line was first adjusted to the desired value. Solids circulation around the unit was then started by adding air to the L-valve. After the solids flow rate around the unit was set, the nitrogen stripping gas was injected into the standpipe. The oxygen concentrations both above and below the stripping gas injection point, system pressure drops, and other system parameters were then measured. The nitrogen flow rate was then increased again.

This procedure was continued in a stepwise fashion until the oxygen concentration in the stripping section was reduced to zero.

Solids flow rates were determined by measuring the solids particle velocity at the standpipe wall. This solids velocity was correlated with the actual solids flow rate through the downcomer in a solids flow test. In the test, the solids flow rate was determined by collecting the solids in a container over a measured time interval and then weighing the solids. During each solids flow rate measurement, the solids particle velocity at the downcomer wall was measured by timing the particle velocity between two marks, 12 inches (0.3 meters) apart, on the wall of the standpipe.

The gas system used in the stripping study was an air-nitrogen system. Air was used as the L-valve aeration gas, the lift-line conveying gas, and the fluidizing gas in the bed above the standpipe. Nitrogen was used only as the stripping gas. With the oxygen analyzer sensors located above (Taps 1A and 1B) and below (Tap 3) the stripping gas injection point, the oxygen profile in the standpipe could be determined. The direction of the stripping gas flow in the standpipe could also be determined by using the oxygen flow analyzers. If the oxygen concentration above or below the stripping gas injection point fell below 21% (the concentration of oxygen in air), it was known that the stripping gas added to the standpipe went up or down, respectively. In addition, the amount of the standpipe gas flow could also be determined with the aid of the oxygen analyzers as long as the stripping gas added to the standpipe did not split.

RESULTS AND DISCUSSION

To understand what happens when stripping gas is added to a standpipe, it is helpful to consider the pressure-drop balance around the equipment. The pressure drops around the unit are illustrated schematically in Figure 5. The high-pressure point in the system was nearly always at the L-valve aeration point. The low-pressure common pressure point was at the top of the solids receiver. Therefore, the pressure-drop balance is such that the sum of the L-valve aeration section, L-valve, lift line, and bend pressure drops must equal the sum of the vessel and standpipe pressure drops:

$$\begin{aligned} \Delta P_{\text{vessel}} + \Delta P_{\text{standpipe}} &= \Delta P_{\text{aeration}} \\ &+ \Delta P_{\text{lift line}} + \Delta P_{\text{bend}} + \Delta P_{\text{L-valve}} \end{aligned} \quad (1)$$

Together, the standpipe-vessel pressure drop constitutes the dependent part of the pressure drop loop. Its pressure drop will adjust to exactly balance the pressure drop produced by the sum of the four pressure-drop components on the

independent side of the loop. The standpipe pressure drop, however, was the dependent loop pressure-drop component that actually did the adjusting. The pressure drop across the fluidized bed was always constant, and the pressure drop across the solids receiver was negligible compared with the standpipe and fluidized-bed pressure drops. Therefore Equation 1 may be written as -

$$\Delta P_{\text{standpipe}} = \Delta P_{\text{aeration}} + \Delta P_{\text{L-valve}} + \Delta P_{\text{lift line}} + \Delta P_{\text{bend}} - C \quad (2)$$

where C is the constant pressure drop across the fluidized bed and the solids receiver vessels. Because every run was made at a constant lift-line conveying gas flow rate and constant solids flow rate, all terms on the right-hand side of Equation (2) are constant. This means that the total standpipe pressure drop was constant throughout a run.

Relative Velocity Model

A standpipe that operates in a moving, packed-bed regime and that has stripping gas added to it can be analyzed by using a relative gas-solids velocity concept. This concept was used to model the stripping of solids in the standpipe. The objectives of this model were to predict the observed behavior of the standpipe and the amount of stripping gas needed to completely strip the standpipe. A discussion of the relative velocity model and how it can be used to analyze the stripper operation is given below.

As stated above, the standpipe pressure drop automatically adjusts to match the pressure drop generated by the independent side of the pressure-drop loop. The standpipe pressure drop is proportional to the relative velocity between solids and gas in the standpipe. Therefore, the standpipe pressure drop is adjusted by the changing of the relative gas-solids velocity in the standpipe.

In this investigation, the pressure at the bottom of the standpipe was always higher than the pressure at the top of the standpipe. For the pressure drop to be in this direction, the relative gas-solids velocity, V_r , must be such that the gas is flowing upward relative to the solids. This can be accomplished in two ways. The gas can be flowing down the pipe relative to the pipe wall, but at a velocity, V_g , less than the solids velocity, V_s ; or the gas can be flowing up the standpipe relative to the pipe wall. These two cases are schematically illustrated in Figure 6.

In the first case, V_g and V_s are flowing down the pipe, and -

$$V_r = V_s - V_g \quad (3)$$

In the second case, the gas is flowing countercurrently to the solids, and -

$$V_r = V_s + V_g \quad (4)$$

The results of a typical run in which gas was initially travelling down the standpipe are shown in Figure 7. When nitrogen stripping gas was added to the standpipe and the gas was initially travelling down the standpipe, the oxygen concentration measured at Tap 3 below the stripping gas injection point (SGIP) decreased immediately. As more nitrogen stripping gas was added to the standpipe, the oxygen concentration above the SGIP (Taps 1A and 1B) remained constant for some time and then rapidly decreased to zero at the same point that the oxygen concentration below the SGIP reached zero.

The results of a run in which the gas was initially travelling up the standpipe are shown in Figure 8. The results are exactly the opposite of those shown in Figure 7. For this case, the oxygen concentration at Taps 1A and 1B started to decrease immediately upon the addition of the nitrogen stripping gas (Figure 8). The oxygen concentration at Tap 3 below the SGIP remained constant for some time and then dropped to zero.

This behavior can be explained with the aid of Figure 9, which is a schematic representation of the Configuration I-type stripping section, and the smaller diameter standpipe below it shown in Figure 2. For a constant solids flow rate in the standpipe, the solids will have a constant linear velocity, V_s . This constant solids flow rate is denoted by the length of the heavy-line arrows in Figure 9. The solids linear velocity in the stripping section is lower than V_s in the standpipe below it, because the diameter of the stripping section is larger. This is illustrated by the length of the arrows representing V_s in both sections. The dotted lines in Figure 9 indicate the direction and magnitude of the linear gas velocities, V_g , for various stripping gas flow rates in both the stripper and the standpipe section.

Case I in Figure 9 is for gas travelling down with the solids; this is the case that applies to Figure 7. In this case, the solids are travelling downward at a constant flow rate, with the gas travelling downward relative to the standpipe wall.

Assume that the dotted arrows designated "O" for Case I in Figure 9 indicate the magnitude and direction of V_g in both the stripper and the standpipe when no nitrogen stripping gas is added to the downcomer. When the nitrogen stripping gas is added to the bottom of the stripper, the pressure drop in the standpipe above the SGIP rises, while the pressure drop in the standpipe below the SGIP falls (Figure 10). The total standpipe pressure drop, however, remains constant. Again, the total standpipe pressure drop must be constant to balance the constant pressure drop in the independent part of the pressure-drop loop shown in

Figure 5. The pressure drop in the standpipe above the SGIP rises because the pressure at the SGIP rises relative to the pressure at the top of the standpipe when stripping gas is added. Because the pressure at the SGIP rises, the standpipe pressure drop below the SGIP falls.

When stripping gas is added to the standpipe, V_r increases in the standpipe stripping section and decreases in the standpipe section below the SGIP. This is because pressure drop is proportional to V_r in a standpipe. Arrows designated "1" in Figure 9 represent the gas velocities in the stripper and the standpipe below it when a small amount of stripping gas is added to the standpipe. The amount of gas being carried down the standpipe in the stripping section decreases at condition "1" relative to condition "0" to increase V_r , and hence, the pressure drops in this section as stripping gas is added. Because of this decrease, however, the amount of gas flowing down the standpipe section below the SGIP increases to decrease V_r in that section. This also means that all of the stripping gas added to the standpipe at "1" flows down with the solids in the section below the SGIP.

Because the gas being carried down by the solids is air (from the fluidized bed above the stripper), the amount of air carried down the pipe decreases when stripping gas is added to the stripper. As more stripping gas is added to the system -

1. The stripper pressure drop increases.
2. V_r increases in the stripper.
3. The amount of air being carried down the stripping section decreases even more.

This trend continues until no air is carried down the standpipe with the solids (arrows designated "3" in Figure 9). Note that at this point, $V_g = 0$. If more stripping gas is added, the stripper pressure drop rises, again necessitating an increase in V_r . However, in order for V_r to increase, the gas must now move up relative to the stripper wall. This gas flow can only come from the stripping gas added to the standpipe. Thus, nitrogen now moves up the stripper as well as down the lower standpipe. At this point the air from the fluidized bed is completely stripped, i.e., it cannot travel down the standpipe.

This explains the curves for sample Taps 1A and 1B (in the stripper) in Figure 7. The constant 21%-oxygen-concentration portion of the curve corresponds to stripping gas flow rates for which the relative velocity in the stripper is increasing, but the air velocity down the stripper is decreasing. When the stripping gas flow reaches a rate at which the stripper pressure drop dictates that gas must move up relative to the stripper wall, nitrogen rises through the stripper, and the oxygen concentration drops sharply.

In the standpipe section below the SGIP, the first bit of stripping gas causes the pressure drop, and thus the relative velocity, to decrease. This means that the gas velocity in this section increases. The increase in gas velocity occurs because the entire amount of stripping gas added to the pipe goes downward with the air from the stripping section. Because the nitrogen goes downward, it dilutes the air from the stripper above; therefore the oxygen concentration in the standpipe below the SGIP decreases. As more stripping gas is added, the gas travelling down the standpipe is diluted more and more. This explains the curve of sample Tap 3 (Figure 7). When point "3" is reached in Figure 9 (i.e., where $V_g = 0$), the nitrogen stripping gas splits. Nitrogen then travels both up the stripper and down the standpipe below the SGIP.

The case for which gas is initially travelling up the standpipe relative to the standpipe wall can also be analyzed with the aid of Figure 9. At point "0" the air is moving upward in both the lower standpipe and the stripper. When stripping gas is added to the stripper, the stripper pressure drop rises, and the pressure drop across the lower standpipe falls. Thus, the V_r in the stripper rises, and the V_r in the lower standpipe decreases. The V_r in the stripper can increase only if more gas travels up the stripper. Therefore, all the nitrogen that is initially added goes up the stripping section diluting the air already moving upward. This explains the initial drop in oxygen concentration at Taps 1A and 1B in Figure 8.

The pressure drop falls in the lower standpipe; therefore the amount of air moving up the pipe has to decrease. As more stripping gas is added, this trend continues until no air moves up the pipe (point "3" in Figure 9). As a little more stripping gas is added, the decreasing pressure in that section causes gas to move downward. This gas can only come from the stripping gas (nitrogen), which is why Tap 3 remains at a constant oxygen concentration initially and then falls.

From the above explanation it is evident that in a packed bed the air can be stripped with nitrogen whether the air is initially moving upward or downward. The actual stripping section is below the SGIP in the former case, and is above it in the latter.

Based on the relative velocity model, a computer program was developed to predict the amount of stripping gas required to strip void gases from a moving packed bed of solids. The following set of equations were used in the program.

The relationship between pressure drop, relative velocity, and voidage in a packed bed is given by the Ergun¹ equation. The relative velocity form of this equation that applies in the standpipe is -

$$g_c \frac{\Delta P}{L} = \frac{150\mu (1 - \epsilon)^2 V_r}{(\phi D_p)^2 \epsilon^2} + \frac{1.75 \rho_g (1 - \epsilon) V_r^2}{(\phi D_p) \epsilon} \quad (5)$$

The familiar relative velocity equations also apply:

$$V_r = V_s - V_g \quad (6)$$

$$= \frac{W_s}{(1 - \epsilon) \rho_p A} - \frac{W_g}{\epsilon A \rho_g} \quad (7)$$

(gas traveling down the downcomer)

$$V_r = V_s + V_g \quad (8)$$

$$= \frac{W_s}{(1 - \epsilon) \rho_p A} + \frac{W_g}{\epsilon A \rho_g} \quad (9)$$

(gas traveling up the downcomer)

A third equation relates the voidage to the relative velocity:

$$\epsilon = \epsilon_0 + K_1 V_r \quad (10)$$

The parameters ϵ_0 and K_1 are determined experimentally.

For a moving packed bed, the pressure drop per unit length must be less than that at which the solids become fluidized. Therefore, Equation 5 is subject to the following constraint:

$$\frac{\Delta P}{L} < \left(\frac{\Delta P}{L} \right)_{mf} \quad (11)$$

Similarly, the relative velocity must be less than the minimum fluidization velocity, so Equations (6), (7), (8), and (9) are subject to the constraint -

$$V_r < V_{mf} \quad (12)$$

This system of equations is solved simultaneously for V_r , ϵ , and W_g in the sections above and below the SGIP for various stripping gas flow rates. When $W_g = 0$ in the stripping section, the standpipe is considered to be stripped.

The relative-velocity computer program was used to predict the amount of nitrogen needed to strip for several of the runs made in the investigation. Figures 8 and 11 through 18 show the agreement between the experimental data and the model predictions for a variety of different stripper diameters and solid flow rates for both up-flow and down-flow of standpipe gas. Operating conditions for these runs are shown in Table 3. A comparison of the experimental and predicted stripping gas requirements for several selected runs is shown in Table 4. The results indicate that the model generally predicts the data to within $\pm 20\%$.

Effect of Stripping Gas Injection Location

The location of the SGIP in a standpipe affects the amount of gas needed to strip. It does so because this changes the pressure drop distribution in the standpipe. Thus, the pressure drops above and below the SGIP change. This changes the relative velocity in each section and, therefore, the amount of gas needed to strip. Because of the generally good agreement between the relative velocity model and the experimental data, the relative-velocity model was used to determine the effect of changing the SGIP location on the amount of nitrogen required to strip. The results are shown in Figure 19 (for gas travelling down with the solids) and Figure 20 (for gas travelling up the standpipe).

The two plots show that moving the SGIP reduces the amount of gas needed to strip in a standpipe. For gas travelling down the standpipe, moving the SGIP closer to the top of the standpipe reduced the amount of stripping gas needed. As the SGIP was "moved" upward, the $\Delta P/L$ was increased in the section above the SGIP, which increased the V_r in that section. Increasing V_r caused the V_g to adjust to a value closer to zero, which reduced the stripping gas requirement.

For gas travelling up the standpipe, the stripping section is actually below the SGIP. Therefore, moving the SGIP toward the bottom of the standpipe reduced the stripping gas requirement. Again, this is because the $\Delta P/L$ in the stripping section was reduced by lowering the SGIP. This decreased V_r (and therefore V_g) and reduced the stripping gas requirement.

In actual practice, stripping efficiency may fall off if the SGIP is located too close to the ends of the standpipe. This is because there may be a minimum standpipe length necessary for complete stripping because of mixing, diffusion, or other factors.

Effect of Pressure Drop

From the previous discussion, the importance of the pressure drop across the stripper is obvious. The pressure drop fixes the relative velocity in the standpipe, which in turn determines how much stripping gas is needed to strip. The pressure drop also determines whether the gas will go up or down. If the pressure drop across the stripper is low, the gas can travel down the standpipe with the solids and still generate the required pressure drop. If the pressure drop is high, however, the gas will have to pass up the standpipe to generate the pressure drop.

The effect of pressure drop on the direction of gas flow can be seen by comparing Figure 8 with Figure 11. For the run depicted in Figure 8, -20+40 mesh Ottawa sand at a flow rate of 10,000 lb/hr (4536 kg/hr) was stripped in an 8-inch (20.3 cm) diameter stripper. To satisfy the pressure drop requirements in the independent side of the pressure-drop loop, the gas was travelling up the standpipe.

For the run represented in Figure 11, the pressure drop in the stripper was decreased for the same material and approximately the same solids flow rate. In this run the pressure drop was low enough so that the gas travelled down with the solids; when stripping gas was added the oxygen concentration at Tap 3 dropped first.

Effect of Solids Flow Rate

The effect of solids flow rate on the amount of stripping gas needed to strip is presented in Figures 12, 13, and 14. The runs represented by these figures were made with -14+80 mesh Ottawa sand in the 8-inch (20.3 cm) diameter stripper with gas flowing down with the solids. Because of the difficulty in keeping the same pressure drop across the stripper for changing solids feed rates, the pressure drop across the stripper was allowed to vary. Because the pressure drop across the lift line increases with solids flow rate at a constant lift-line gas velocity, the pressure drop across the standpipe will also increase with solids flow rate. Increasing the stripper pressure drop would have the effect of decreasing the amount of gas needed for stripping. However, it was found that the amount of gas needed to strip increased as the solids flow rate increased despite the non-constant pressure-drop effect. Thus, stripping gas requirements increase with solids flow rate for gas travelling down with the solids.

For most standpipe systems, gas will flow down with the solids. However, when gas travels up the standpipe, increasing the solids flow rate has the opposite effect. Increasing the solids flow rate at a constant stripper pressure drop for gas flowing up results in a decrease in stripping gas requirements. This can be seen with the aid of Figure 21. Because the pressure drop across the stripper is constant, V_r is also constant. However because V_s increases, V_g decreases, and less gas is required to strip.

Effect of Stripper Diameter

The effect of stripper diameter on the amount of gas needed to strip also depends upon the direction of standpipe gas flow. For gas flowing down with the solids, the amount of gas needed to strip increases as the standpipe diameter is decreased at a constant stripper pressure drop (Figure 22). The curves in this figure were generated from the relative-velocity model computer program previously described. More gas is needed to strip because as the standpipe diameter decreases, V_s increases. For a constant stripper pressure drop, V_g also increases. The increase in V_g more than offsets the diameter effect, so the amount of gas required to strip increases.

For gas travelling up the standpipe, increasing the standpipe diameter at a constant stripper pressure drop increases the amount of stripping gas needed to completely strip (Figure 23). The curves in this figure were also generated from the relative velocity model computer program.

When the diameter is decreased for this case (at constant stripper pressure drop), V_s increases, V_g decreases, and the stripping gas requirement is reduced.

Stripping in Fluidized Standpipes

In a few runs, the standpipe $\Delta P/L$ above the SGIP became high enough that V_r exceeded V_{mf} and the solids began to fluidize in that section. To analyze fluidized-bed stripping, two cases must again be considered: gas travelling down with the solids and gas travelling up the standpipe.

Gas Down. During a run made using -80+170 mesh Ottawa sand, the solids in the 8-inch (20.3 cm) diameter stripper became fluidized midway through the run. The oxygen concentration curves for this run are shown in Figure 24. Gas was travelling down the standpipe with the solids in this run.

When the solids above the SGIP became fluidized, the pressure drop above the SGIP could no longer increase when more stripping gas was added to the standpipe because, under fluidized conditions, $\Delta P/L$ does not change with V_r for a fluidized bed over a wide range. This is schematically shown in Figure 25.

Because the upper standpipe pressure drop could not increase, the pressure drop below the SGIP could not drop. Therefore, additional stripping gas added to the standpipe could not go down the standpipe with the solids as it could in the packed-bed standpipe. The additional nitrogen added to the standpipe then had to pass up the standpipe in the form of bubbles. This bubble flow was indeed observed in the standpipe above the SGIP after the standpipe became fluidized. The bubbles were also observed to increase in size and speed as stripping gas was increased. In addition, the oxygen concentration at Tap 1A (the lower tap) in the standpipe above the SGIP fell rather rapidly to zero. The oxygen concentration at the upper tap, however, did not fall to zero until later. This phenomenon can be explained as follows.

When the standpipe above the SGIP becomes fluidized, the pressure drops above and below the SGIP remain essentially constant. Any excess stripping gas added to the standpipe will therefore travel up the standpipe as bubbles. However, before the standpipe above the SGIP became fluidized, oxygen was still travelling down the standpipe with the solids.

For a very brief period oxygen in the air is travelling down the standpipe in the emulsion phase, while nitrogen is travelling up in the bubble phase. The nitrogen in the bubble phase and the oxygen in the emulsion phase then interchange over the height of the stripper. The result of this situation is that there is an oxygen gradient in the stripper wherein the oxygen concentration is lower at the bottom than at the top. This condition exists until the nitrogen travelling up the standpipe effectively "absorbs" all of the oxygen and the standpipe is stripped.

Gas Up. A run was also made with gas initially travelling up the standpipe in which the standpipe above the SGIP became fluidized during the run. This run was made with -40+80 mesh Ottawa sand in the 4-inch (10.2 cm) diameter Configuration II standpipe. The oxygen concentration versus nitrogen flow rate curves for this run are shown in Figure 26.

When the standpipe section above the SGIP became fluidized in this run, further stripping could not be achieved. When more stripping gas was added to the standpipe, the pressure drop above the SGIP did not increase because of the $\Delta P/L$ versus V_r relationship for a fluidized bed, as discussed above. Thus the pressure drop below the SGIP remained constant. Because V_r was constant, V_g was also constant, and therefore the oxygen concentration in the standpipe below the SGIP remained constant at 21%. This can be seen in Figure 26.

The oxygen concentration above the SGIP leveled off after the upper standpipe section became fluidized. If more nitrogen were added to the standpipe, the oxygen concentration in the upper standpipe would be expected to gradually fall off. However, no matter how much nitrogen is added, air (and therefore oxygen) will continue to flow up the standpipe, and

complete stripping will not occur. Thus, for the case of gas flowing up a standpipe in fluidized-bed flow, the interstitial gas cannot be stripped.

Stripping-Section Design

The relative velocity model for the moving packed bed predicts, and the data show, that the minimum amount of stripping gas is needed when $V_g = 0$ initially in the standpipe. At this condition, solids would be falling through stagnant gas, and theoretically no stripping gas would be needed. Realistically, however, this will not occur because solids flow rates do not stay constant, and there is a certain degree of mixing and diffusion in a "real" standpipe. However, for optimum stripping a standpipe should be operated as close to $V_g = 0$ as possible. Therefore, $V_g = 0$ is the criterion for optimum stripping section design. This criterion, used in conjunction with the relative velocity model, can be used to design a moving packed-bed stripper.

In a process in which a stripping section is needed, the following information is usually given:

1. System
 - o The total pressure drop, ΔP_T , across the standpipe.
2. Solids
 - o Particle Density, ρ_p
 - o Solids mass flow rate, w_s
 - o Particle size, d_p
 - o Sphericity, ϕ
3. Gas
 - o Gas Density, ρ
 - o Gas Viscosity, μ

Also known, or easily obtainable, would be the pressure drop per unit length at which the solids became fluidized, $(\Delta P/L)_{mf}$, as well as the minimum fluidization velocity of the solids, V_{mf} , K_1 , and ϵ_0 .

The following need to be determined:

1. The standpipe diameter, D_T
2. The standpipe length, L

For optimum stripper design, $V_g = 0$. Equations (6) and (7) then both become -

$$V_r = V_s \quad V_r < V_{mf} \quad (13)$$

$$= \frac{W_s}{(1 - \epsilon) \rho_p A} \quad (14)$$

$$= \frac{4W_s}{(1 - \epsilon) \rho_p D_T^2 \pi} \quad (15)$$

The design procedure is as follows:

1. Pick the $\Delta P/L$ desired in the standpipe. Because the ΔP_T is known, this sets the standpipe length. The value used is arbitrary as long as it is less than $\Delta P/L)_{mf}$. For a fixed ΔP_T , however, the higher the $\Delta P/L$ value selected, the shorter the standpipe will be. Also, the $\Delta P/L$ value selected should not be too near $\Delta P/L)_{mf}$, so that operating changes or upsets will not cause the standpipe $\Delta P/L$ to exceed $\Delta P/L)_{mf}$. A logical $\Delta P/L$ value would be in the range of $2/3$ to $3/4 \Delta P/L)_{mf}$. This would provide a flexible stripper design.
2. Using the $\Delta P/L$ value from Step 1, calculate the standpipe V_r and ϵ by solving Equations (5) and (10) simultaneously.
3. Using the value for V_r calculated in Step 2, determine the standpipe diameter for Equation (15).

Porous Particles

The runs in which successful stripping of the interstitial gas was accomplished were made with essentially nonporous particles, i.e., sand and siderite. Stripping tests were also conducted with porous -20+40 mesh FMC char particles. However, it was found that it was nearly impossible to completely strip the gas between the char particles before the standpipe became fluidized.

As discussed previously, it is possible for fluidization to occur in the stripping section of the standpipe with nonporous particles. For example, if gas is initially travelling downward in the standpipe, fluidization will occur if V_s in the standpipe is greater than V_{mf} for the material. if V_s is less than V_{mf} , stripping will occur before fluidization begins.

For the tests conducted with the porous char particles, gas was always travelling downward initially. For all of these tests, fluidization occurred in the standpipe before complete stripping occurred, even when the V_s of the char in the standpipe was less than V_{mf} for the char. The incomplete stripping

is apparent from the oxygen concentration versus stripping gas flow rate curve shown in Figure 27.

The reason for this anomaly is apparently due to diffusion of the trapped air in the pores of the char into the bulk of the gas stream. Even though a standpipe filled with char can be stripped in the classical sense (i.e., when the nitrogen stripping gas is splitting and travelling both upward and downward in the standpipe), the oxygen in the pores in the particles can still diffuse into the interstitial gas.

If diffusion is indeed occurring in the stripper, then increasing the stripper length should allow greater air-nitrogen diffusional interchange and thus a greater degree of stripping. Lowering the solids velocity in the stripper (i.e., increasing the residence time in the stripper) should also result in a greater degree of stripping. That this is indeed the case has been demonstrated in tests with FMC char. In these tests, the standpipe was stripped with nitrogen for three different solids flow rates so that in each case

$V_s < \frac{V_{mf}}{\epsilon}$. $\frac{V_{mf}}{\epsilon}$ for the FMC char was determined to be approximately 0.7 ft/s. The tests were then repeated for a stripping gas injection location 3 feet lower than in the previous tests. The results of these tests are shown in Figure 28. In this figure, the oxygen concentration in the standpipe below the SGIP, measured at incipient fluidizations in the standpipe, is plotted versus V_s for both sets of runs described above. For both sets of runs, the results tend to support the diffusion hypothesis explained previously. The oxygen concentration in the standpipe below the SGIP was found to decrease with decreasing V_s . It was also found to decrease when the SGIP was lowered.

The relative velocity model does not predict stripping gas requirements well for stripping with porous FMC char. Therefore, in future work, a diffusion term will be added to the relative velocity model to improve its accuracy in predicting stripping gas requirements with porous particles.

CONCLUSIONS

1. The void gas in a standpipe operating in a moving packed-bed regime can be stripped upon the addition of stripping gas to the standpipe when gas is travelling up or down the standpipe.
2. The minimum amount of stripping gas is needed when the gas velocity in the standpipe is zero. Theoretically, no gas is needed if $V_g = 0$ because solids are falling through stagnant gas.
3. The void gas in a standpipe operating in a fluidized-bed mode can be stripped upon the addition of stripping gas if the standpipe gas is initially travelling down with the solids.

4. The void gas in a standpipe operating in a fluidized-bed mode cannot be stripped upon the addition of stripping gas if the standpipe gas is initially travelling up the standpipe.
5. The relative velocity model of solids and gas flow in a moving packed bed appears to explain the observed behavior of the standpipe and predicts the stripping gas requirements within $\pm 20\%$.
6. Stripping gas requirements for gas travelling down the standpipe with the solids can be decreased by -
 - o Increasing the stripping section pressure drop
 - o Raising the SGIP
 - o Lowering the solids feed rate
 - o Increasing the stripper diameter.
7. Stripping gas requirements for gas travelling up the standpipe can be decreased by -
 - o Decreasing the stripping section pressure drop.
 - o Lowering the SGIP.
 - o Raising the solids feed rate.
 - o Decreasing the stripper diameter.

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NOTATION

A = cross-sectional area of standpipe
 C = constant vessel pressure drop
 d_{pi} = particle size of a particular size fraction, i
 $\bar{D}_p$ = average particle size
 D_T = standpipe diameter

K_1 = voidage slope constant
 L = standpipe length
 ΔP = pressure drop
 $\Delta P/L$ = pressure drop per unit length
 $\Delta P/L)_{mf}$ = pressure drop per unit length at minimum fluidization
 V_g = linear gas velocity
 V_{mf} = minimum fluidization velocity
 V_r = gas-solids relative velocity
 V_s = solids velocity
 W_g = mass flow rate of gas
 W_s = mass flow rate of solids
 X_i = weight fraction of solids of size d_{pi}
 ϵ = voidage
 ϵ_o = minimum packed-bed voidage
 μ = viscosity of gas
 ρ_g = gas density
 ρ_p = solids particle density
 ϕ = particle sphericity
 π = pi

Table 1. OXYGEN ANALYZER TAP LOCATIONS

Run No.	x, in. (cm)	y, in. (cm)	z, in. (cm)
VGS-24	45 (114.3)	57 (144.8)	56 (142.2)
VGS-27	45 (114.3)	57 (144.8)	56 (142.2)
VGS-29	45 (114.3)	57 (144.8)	56 (142.2)
VGS-32	32 (114.3)	57 (144.8)	56 (142.2)
VGS-33	45 (114.3)	57 (144.8)	56 (142.2)
VGS-35	45 (114.2)	57 (144.8)	56 (142.2)
VGS-47	27 (68.6)	59 (149.9)	56 (142.2)
VGS-48b	27 (68.6)	59 (149.9)	56 (142.2)
VGS-52	27 (68.6)	59 (149.9)	56 (142.2)
VGS-55	19.5 (49.5)	44 (111.8)	63 (160)
VGS-59	48 (121.9)	96 (243.8)	48 (121.9)
VGS-61	48 (121.9)	96 (243.8)	48 (121.9)
VGSA-14	54 (137.2)	123 (312.4)	91 (231.1)

Table 2. PHYSICAL CHARACTERISTICS OF SOLIDS TESTED

Material	Size Range, Mesh	$\bar{D}_p^*$ ft (μ)	ρ_p , lb/ft ³ (k/m ³)
Ottawa Sand	-20+40	0.00228 (695)	163.8 (2624)
Ottawa Sand	-40+80	0.000775 (236)	162.3 (2607)
Ottawa Sand	-80+170	0.000411 (125)	162.1 (2596)
Siderite Ore	-20+60	0.001849 (564)	233.5 (3739)
FMC Char	-20+60	0.00118 (358)	163.9 (2624)

Table 3. OPERATING CONDITIONS FOR MODEL-PREDICTING RUNS

Run No.	Material	Particle Size Range	Solids Circulation Rate, lb/hr (kg/hr)	Stripper Diameter, in. (cm)	Stripper Length, ft (m)	Direction of Gas Flow
VGS-27	Ottawa Sand	-20+40	10,000 (4,536)	8 (20.3)	7.25 (2.2)	Up
VGS-29	Ottawa Sand	-20+40	9,500 (4,309)	8 (20.3)	7.25 (2.2)	Down
VGS-32	Ottawa Sand	-40+80	10,000 (4,536)	8 (20.3)	7.25 (2.2)	Down
VGS-33	Ottawa Sand	-40+80	15,000 (6,804)	8 (20.3)	7.25 (2.2)	Down
VGS-35	Ottawa Sand	-40+80	4,950 (2,245)	8 (20.3)	7.25 (2.2)	Down
VGS-47	Ottawa Sand	-40+80	5,330 (2,418)	8 (20.3)	7.25 (2.2)	Down
VGS-52	Ottawa Sand	-40+80	5,300 (2,404)	6 (15.2)	7.25 (2.2)	Down
VGS-55	Ottawa Sand	-40+80	5,500 (2,495)	4 (10.2)	7.25 (2.2)	Down
VGS-61	Siderite	-20+60	6,500 (2,948)	4 (10.2)	12.8 (3.9)	Up

Table 4. COMPARISON OF EXPERIMENTAL WITH
PREDICTED NITROGEN STRIPPING
GAS FLOW RATES

<u>Nitrogen Stripping Gas Flow Rate, Actual CF/min</u> <u>(actual m³/min)</u>			
<u>Run No.</u>	<u>Experimental</u>	<u>Model Prediction</u>	<u>% Difference</u> *
VGS-27	2.27 (0.064)	2.32 (0.066)	2.2
VGS-29	0.89 (0.025)	0.97 (0.027)	9.0
VGS-32	0.56 (0.016)	0.67 (0.019)	19.6
VGS-33	0.82 (0.023)	0.94 (0.027)	14.3
VGS-35	0.36 (0.01)	0.365(0.01)	1.4
VGS-47	0.37 (0.01)	0.34 (0.01)	8.1
VGS-52	0.37 (0.01)	0.34 (0.01)	8.1
VGS-55	0.33 (0.009)	0.34 (0.01)	3.0
VGS-61	0.45 (0.013)	0.44 (0.012)	2.2

* % difference =
$$\frac{(\text{Predicted Value} - \text{Experimental Value})}{\text{Experimental Value}} \times 100$$

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Figure 1. VOID-GAS STRIPPING EQUIPMENT

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Figure 2. STANDPIPE CONFIGURATIONS TESTED

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Figure 3. OXYGEN ANALYZER SENSOR LOCATIONS
FOR STANDPIPE CONFIGURATION 1

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Figure 4. OXYGEN ANALYZER SENSOR LOCATIONS
FOR STANDPIPE CONFIGURATION 2

Figure 5. PRESSURE DROPS AROUND THE STRIPPING EQUIPMENT LOOP

CASE I
GAS FLOWING DOWNWARD
RELATIVE TO PIPE WALL

CASE II
GAS FLOWING UPWARD
RELATIVE TO PIPE WALL

↑
DIRECTION OF
PRESSURE DROP

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Figure 6. RELATIONSHIP BETWEEN RELATIVE VELOCITY
AND PRESSURE DROP

Figure 7. OXYGEN CONCENTRATION VERSUS NITROGEN FLOW RATE
 (Run No. VGS-24, Gas Down)

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Figure 8. OXYGEN CONCENTRATION VERSUS STRIPPING GAS FLOW RATE
(Run No. VGS-27, Gas Up)

Figure 9. RELATIVE GAS-SOLIDS VELOCITIES IN THE STRIPPER AND STANDPIPE

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Figure 10. STANDPIPE PRESSURE DROPS AS A FUNCTION OF STRIPPING GAS FLOW RATE

Figure 11. OXYGEN CONCENTRATION VERSUS NITROGEN FLOW RATE
 (Run No. VGS-29, Gas Down)

Figure 12. OXYGEN CONCENTRATION VERSUS NITROGEN FLOW RATE
(Run No. VGS-32, Gas Down)

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Figure 13. OXYGEN CONCENTRATION VERSUS NITROGEN FLOW RATE
 (Run No. VGS-33, Sand, Gas Down)

Figure 14. OXYGEN CONCENTRATION VERSUS NITROGEN FLOW RATE
 (Run No. VGS-35, Gas Down)

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Figure 15. OXYGEN CONCENTRATION VERSUS NITROGEN FLOW RATE
 (Run No. VGS-47, Gas Down)

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Figure 16. OXYGEN CONCENTRATION VERSUS NITROGEN FLOW RATE
(Run No. VGS-52, Gas Down)

Figure 17. OXYGEN CONCENTRATION VERSUS NITROGEN FLOW RATE
(Run No. VGS-55, Gas Down)

Figure 18. OXYGEN CONCENTRATION VERSUS NITROGEN FLOW RATE
 (Run No. VGS-61, Gas Up)

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Figure 19. THE EFFECT OF STRIPPING GAS INJECTION LOCATION A79112490
(Gas Down)

Figure 20. EFFECT OF STRIPPING GAS INJECTION LOCATION
(Gas Up)

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Figure 21. RELATIVE VELOCITY CHANGES AS A RESULT OF CHANGING SOLIDS FLOW RATES

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Figure 22. THE EFFECT OF STRIPPER DIAMETER ON STRIPPING GAS REQUIREMENTS (Gas Down)

Figure 23. THE EFFECT OF STRIPPER DIAMETER ON STRIPPING GAS REQUIREMENTS (Gas Up)

Figure 24. OXYGEN CONCENTRATION VERSUS NITROGEN FLOW RATE
 (Run No. VGS-48B; Gas Down, Fluidized)

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Figure 25. BED DENSITY VERSUS RELATIVE VELOCITY
FOR A FLUIDIZED BED

Figure 26. OXYGEN CONCENTRATION VERSUS NITROGEN FLOW RATE
(Run No. VGS-59, Gas Up, Fluidized)

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Figure 27. OXYGEN CONCENTRATION VERSUS NITROGEN FLOW RATE
(20/60 FMC Char, Gas Down)

* Measured from the top of the standpipe.

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Figure 28. OXYGEN CONCENTRATION VERSUS SOLIDS VELOCITY IN THE STRIPPER FOR TWO STRIPPING GAS INJECTION LOCATIONS (20/60 FMC Char, Gas Down)