

Effect of sub-layer water saturation on two-layer sand fluidization

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SUMMARY

A fluidized bed is a system where solid particles, like sand, are made to behave like a liquid by blowing air upwards through them. Despite being used widely in power plants, manufacturing coatings, and chemical processing since the 19th century, the construction of fluidized beds remains imperfect. Moisture in the granular bed is an unresolved obstacle to efficient fluidization, as previous studies established that moisture significantly hinders the performance of a fluidized bed. Currently, most academic studies and industrial fluidized beds focus on a single layer with homogenous moisture content, and not two different layers. Here, we tested whether injecting air into a dry sand bed placed over a water-saturated sand sub-layer would fluidize the top dry layer. We hypothesized that a layer of wet sand, regardless of water saturation level, underneath dry sand will reduce fluidization efficacy because areas of greater moisture in porous media reduce gas permeability and stabilize the bottom layer of dry sand. Varying the water content of a sand layer underneath a consistently dry upper layer, we used an image analysis software (ImageJ) to estimate the fluidized area and compared those results to uniform fluidization with a two-sample t-test to compare means. The results showed that even 0.5% of saturation hindered the fluidization of the top layer, meaning that a two-layer fluidized bed of any moisture is not viable. These findings underscore the importance of rigorous moisture control in fluidized bed systems, as even minimal, localized moisture can compromise fluidization performance.

INTRODUCTION

Fluidized beds are essential components in modern industrial processes, being used to coat pharmaceutical tablets, suspend food in transport or heating, and even operate chemical reactors (1,2). These systems rely on the predictable behavior of gas through dry granular media to create a uniform, fluid-like state. However, the presence of moisture can prevent fluidization and cause loss of industrial utility (1). While most research focuses on how moisture affects a single, consistent layer, there is a critical gap in understanding how localized moisture, such as a water saturated sub-layer, impacts the overall system. Understanding the limitations of fluidized beds is vital for ensuring that fluidized beds can be utilized to their maximum potential.

Fluidization is the state of particles being suspended and behaving as a fluid (1). The core concept of a fluidized bed is that the granular bed of solid particles fluidizes when an upward flowing drag force is strong enough to overcome any downward forces (1). When the upwards drag overcomes these downward forces, the grain particles lose contact with each other and begin to oscillate vertically (1,2). Minimum

fluidization velocity is the minimum speed of the gas required to achieve this state of mobilization (3). At speeds above this, we would still consider this a fluidized bed, even though the grains may remain suspended in air higher than at lower speeds (1). In perfect conditions where all the grains are dry, increasing particle density results in a higher minimum fluidization velocity (3,4). Adding water to the sand effectively increases the particle density, which makes it harder to fluidize because it increases the minimum fluidization velocity. Similarly to how the minimum fluidization velocity is impacted by the particle density, the behavior observed in fluidized beds also differs based on particle density. We can grade the visual changes in fluidization through Geldart's classification of particles which classifies fluidization behavior as A (aeratable), B (sand like), C (cohesive), or D (spoutable). Group A particles have very low density and are known as aeratable powders. Group B particles are sand-like powders that fluidize easily once the minimum fluidization velocity or pressure is met. Group C particles are difficult to fluidize, and channel the gas into specific areas due to their interparticle forces. In systems of group C particles, some initial, nonuniform slugging is seen, but with much less intensity than group D particles. Slugging is a term used to describe the unstable flow regime where gas bubbles grow and rise through the solid material, then collapse as the bubble bursts. Group D particles are large and have higher density relative to other particle types, often producing slugging in the fluidized bed (5,6). Separately, three states—pendular, funicular, and capillary—describe the stages of liquid saturation. In the pendular state, grains are held together by capillary forces at contact points. Most of the space between the grains is still filled with air, so very little liquid is present. The funicular, or intermediate stage, behaves differently because the liquid has begun to change the grain's properties. The material becomes more cohesive because the bridges that form from the liquid contacting multiple particles, or pendular bridges, begin to merge. The capillary state is the highest state of saturation, with the space nearly or completely filled with liquid. The liquid creates a capillary suction that pulls the grains together into a solid-like structure. If too much water is added, it can become a slurry that flows like a thick substance (5,7). Since the introduction of liquid bridges together particles, the effective density increases. This greater density results in behavior akin to group C or group D particles, which are more difficult to fluidize.

As described in the liquid saturation classification scheme, the addition of water introduces capillary forces that resist fluidization (8). When air is applied to a fluidized bed, the only forces on a dry grain are the force of gravity from its own mass, and the upwards drag from the air being injected (**Figure 1A**). Wet granular material not only has a greater force of gravity because of its increased mass relative

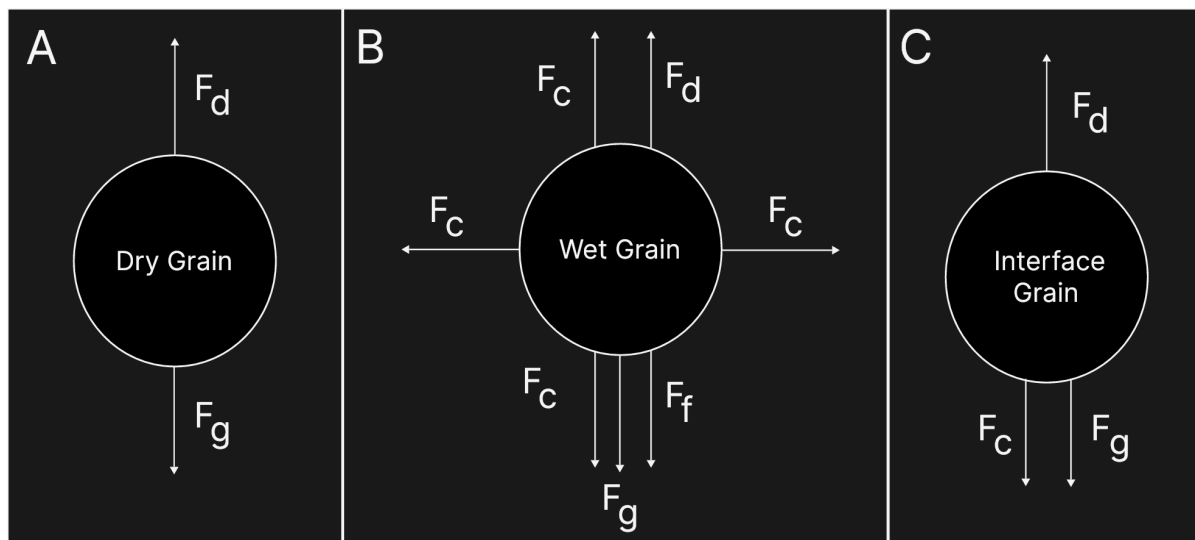


Figure 1. Free body diagrams of the forces on an individual grain at the moment of air injection. Shown here is an (A) individual dry grain, (B) a wet grain, and (C) an interface grain, which is a dry grain on top of a wet grain. F_g represents the force of gravity. F_d represents the upwards drag force coming from the air ejected by the air compressor. F_c represents the capillary forces from being in contact with other wet grains. F_f represents the force of friction exerted by other grains as they try to move upwards.

to dry grains, but they exhibit capillary forces (liquid bridges) on other particles and friction that resists movement (**Figure 1B**). The friction is a result of these capillary forces and increases as the capillary force grows (9,10). In a specific case, a dry grain can be in contact with a wet grain that is between it and the air source at the instant of air injection. The dry grain in this special scenario is an interface grain. This interface grain experiences the same forces as a dry grain, but additionally has a downward capillary force because it is in contact with a wet grain that is vertically beneath it (**Figure 1C**). Wet granular material, such as grain B (wet grain) and grain C (interface grain), experiences more forces that go against the upwards drag force in comparison to dry grains (11,12). Furthermore, water bridges reduce the area that air can permeate through in porous media (8,13,14). This means that not only is wet granular material significantly harder to fluidize, but also that certain areas can experience less of the upwards drag force required to fluidize the bed.

Previous research has focused on the performance of fluidized beds with uniform distribution of moisture, leaving a gap in analyzing the performance of fluidized beds with moisture in only portions of the bed (8). Since the upwards air drag force must still overcome the adhesive forces that the wet grains produce and evenly permeate through the wet porous media, we hypothesized that a sub-layer of wet sand will prevent a top layer of dry sand from achieving fluidization behavior similar to that of standard fluidized beds. To test this, we poured in a mixture of sand and water at various ratios into our fluidization chamber, then poured completely dry sand on top of the wet bottom layer. We took photos and then used an image analysis program (Image J) to compare the results to normal fluidized beds. Our results showed that the addition of moisture to the bottom layer significantly decreased the amount of area that was fluidized and altered the fluidization behavior to that of group C particles. Given these results, we conclude that a fluidized bed with a wet sub-layer likely poses no utility in comparison to standard, fully dry, fluidized beds.

RESULTS

Study design

The hypothesis for our experiment is that moisture in a sub-layer of sand that will cause a fluidized bed to have sub-optimal performance. We made a fluidized bed using a polyvinyl chloride (PVC) network with holes powered by a 125 PSI air compressor. We mixed 1250 g of dry sand with water thoroughly at different levels of water saturation (0% to 1% in increments of 0.1%; 1% to 10% in increments of 1%; 10% to 100% in increments of 10%). We defined saturation levels as a percentage of the dry sand mixed; thus, a saturation level of 10% would be $0.1 \times 1250 \text{ g} = 125 \text{ g}$ of water we added to 1250 g of sand. We spread and layered the sand and water mixture on the fluidization bed and then spread the remaining 1250 g of dry sand on top of the mixture. After injecting air into the bed, we took photos and videos to analyze how much of the bed had fluidized. We classified the behavior according to Geldart's classification (5,6). We conducted 3 trials per 29 different water saturation levels. All trials were compared to the 0% trial results, which served as a control.

Overall trends and changes in performance

We observed that across the 30 water saturation levels tested, 26 showed a significant decrease in fluidized area relative to a completely dry fluidized bed (**Figure 2**). From 0.9% to 100% water saturation, the fluidized area decreased as the water saturation levels increased. The fluidization behavior also changed as the water saturation levels increased, transitioning from uniform fluidization, to channeling, then partial fluidization, minimal fluidization, and lastly slugging.

Water saturation trials with no significant reduction in fluidized area (0% to 0.4%)

We observed that water saturation levels $> 0.4\%$ resulted in decreased fluidized area (**Figure 2**). In contrast, 0% - 0.4% water saturation produced uniform fluidization, but the suspension of sand was higher than the base level because

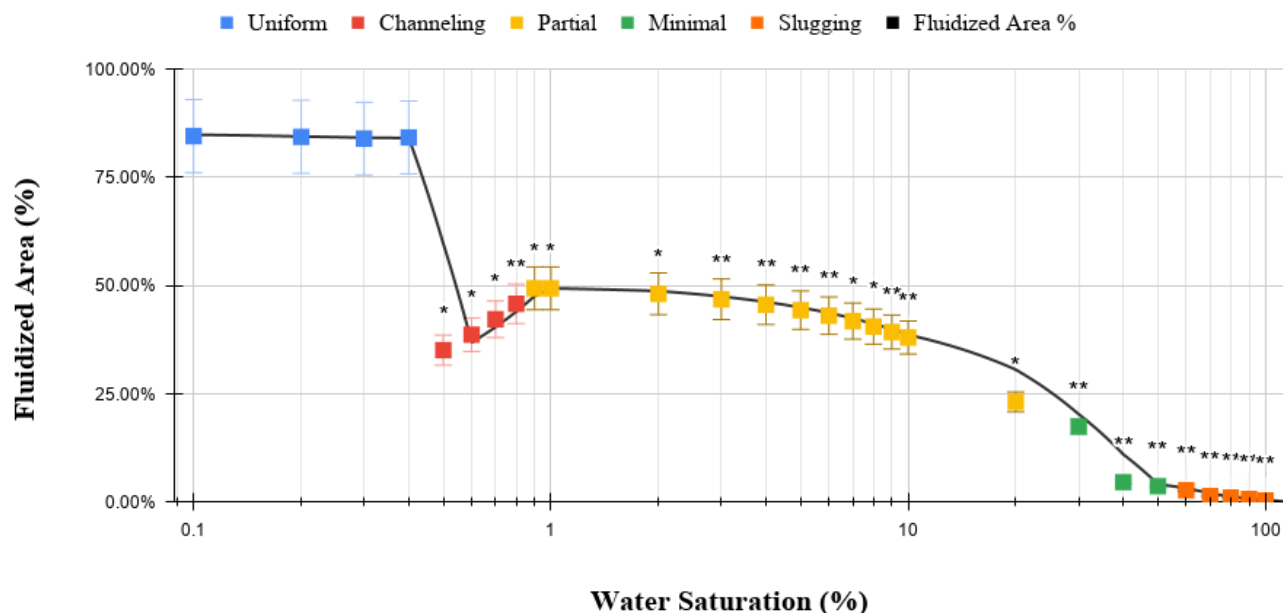


Figure 2. Scatterplot of fluidized area (%) by water saturation (%). 1250 g of dry sand was layered over 1250 g of sand mixed with water at saturation levels ranging from 0% to 100%, and the resulting fluidized area was measured via ImageJ image analysis after air injection at 90 PSI. We classified modes of fluidization based on how much area was under the effect of the observed fluidization, and the behavior observed. A single asterisk represents a p -value of $p < 0.01$, and two asterisks represent a p -value of $p < 0.001$.

the operating pressure (90 PSI) exceeded the minimum fluidization velocity (**Figure 3**). In our preliminary testing, we determined that 70 PSI was the lowest pressure that created an airflow resulting in fluidization; therefore, 70 PSI created the airflow matching the minimum fluidization velocity, which our 90 PSI operating pressure exceeded. We also did not see any visible signs that the sand was wet, as no clumps had formed. We classified the bottom layer at water saturation levels of 0.1% to 0.4% as group B particles in the dry state since there were no visible clumps holding the sand together. The p -values for all trials between 0.1% to 0.4% were greater than the alpha level (0.01) by a substantial amount.

Water saturation trials that exhibited channeling (0.5% to 0.8%)

We begin to see a sharp decrease in fluidized area at 0.5% water saturation (**Figure 2**). At 0.5% water saturation, there was a brief initial moment where the entire top layer uniformly fluidized, but it was quickly redirected and channeled into one area that was strongly fluidized (**Figure 4**). This level of water saturation also resulted in the first trial where we observed the sand beginning to form clumps after being thoroughly mixed with water; therefore any trial at water saturation levels higher or equal to 0.5% can be considered wet. From 0.6% to 0.8%, we observed channeling behavior similar to that of the 0.5% trials; however, there was a slight increase in the area of fluidization as water saturation increased.

Water saturation trials that exhibited partial fluidization (1% to 20%)

Attempts at fluidization in the trials with a water saturation percentage from 1% to 20% resulted in a partial fluidization of the top layer (**Figure 5**). The areas where fluidization occurred were much more dispersed than observed in trials with a

lower water percentage, and they were not concentrated in a particular area. The suspension of sand mimicked the uniform fluidization we observed at 70 PSI, where the air just meets the minimum fluidization velocity. However, the air failed to fluidize the entirety of the top layer and the air flow was noticeably weaker in the areas where it managed to reach the surface. A common trend was that these areas of stagnant sand that were not fluidized appeared in the middle of the fluidized bed. The sides were always fluidized, and there was often a small, fluidized line that ran near the middle, although the direction varied for each trial.

Water saturation trials that exhibited minimal fluidization (30% to 50%)

Water saturation percentages from 30% to 50% produced minimal fluidization in the top layer (**Figure 6**). The affected area of fluidization dropped significantly. The fluidization was extremely limited in area, and we often observed it coming from the sides of the fluidized bed. Trials at 30% and 40% showed small bubbling and air escaping through the top layer, but not enough to fluidize the space. The center was mostly stagnant throughout the trials, especially for the trials at 50%. The mixture of water and sand at 50% also began to resemble a more cohesive mixture, similar to a slurry, but no aggressive eruptions similar to slugging were observed. We therefore classified these water saturation levels to be equivalent to group C particles.

Water saturation trials that exhibited slugging (60% to 100%)

We observed significant changes in fluidization behavior from water saturation percentages 60% and above. Nothing in the top layer of the bed fluidized. The mixture of water and sand at these saturation percentages created a slurry, and we found excess water on top of the mixture



Figure 3. Representative fluidized bed at 0% water saturation. No water was present in the fluidized bed composed of 2500g of sand. 90 PSI of air was injected into the bed (18.5 cm by 21.0 cm). The encircled yellow area represents the fluidized area captured by this photo (321.81 cm²). Other photos at this water saturation level captured fluidized areas of 325.14 cm² and 345.87 cm² and exhibited similar fluidized behavior (n=3).

from 70% and above. Once we injected the air, the top layer did not show any signs of air permeating until after a few seconds, when the air erupted through the top layer, clearing out small holes in the top layer (**Figure 7**). Slugging in the bottom layer was visible through the holes in the top layer, and none of the unaffected stagnant areas of the top layer fluidized or showed any signs of air permeation.

Control experiment

We performed a control experiment to analyze if adding 1250 g of dry sand to a system of only 2500g of dry sand would produce the same inhibitory effect seen in our hypothesis testing. This is meant to replicate the weight of the trial with 100% water saturation, since adding the same weight would allow us to discern if the increase in mass or the capillary forces were preventing fluidization. Adding 1250 g of dry sand to the system increased the pressure drop required in the bed for uniform fluidization because the increase in mass was proportional to the increase in pressure. The formula for pressure drop, the decrease in fluid pressure as a gas or liquid flows upward through a bed of solid particles, is

$$\Delta P = \frac{M_s(1-\epsilon)(p_p - p_f)g}{A} \quad (\text{Equation 1})$$

where ΔP is the pressure drop, M_s is the mass of the solid particles, ϵ is the bed voidage (also called porosity, which is the empty space between solid particles), p_p is the density of the particle, p_f is the density of the gas, g is the acceleration from gravity, and A is the cross sectional area of the bed (1). This equation predicts that for uniform fluidization to be maintained, the pressure drop must be increased as mass increases. This means that the pressure needed to fluidize



Figure 4. Representative fluidized bed at 0.5% water saturation. 6.25 g of water was mixed with 1250 g of dry sand, and 1250 g of dry sand was layered on top of the mixture. 90 PSI of air was injected into the bed (18.5 cm by 21.0 cm). The encircled yellow area represents the fluidized area captured by this photo (140.66 cm²). Other photos at this water saturation level captured fluidized areas of 130.93 cm² and 136.93 cm² and exhibited similar fluidized behavior (n=3).

3750g of dry sand must be greater than the pressure to fluidize 2500g of dry sand. We tested our control experiment using the same operating pressure as the one we used in our main experiment (90 PSI), and we still observed uniform fluidization despite the increase in mass. The results showed fluidized areas of 346.53 cm², 329.71cm², and 313.22cm²; these results are extremely similar to the 0% to 0.4% water saturation trials (**Figure 3**). Complete fluidization of the 3750g bed at 90 PSI indicates that increasing the air pressure from the minimum fluidization pressure of 70 PSI to 90 PSI effectively accounted for the mass added by water in our experiments. Therefore, in our experiment, the increase in mass is not a confounding variable.

DISCUSSION

Our experiment evaluated if fluidized beds are viable in situations where the bed is composed of two layers with the bottom layer being saturated with water. Our hypothesis was that the introduction of moisture into the sub-layer will reduce the fluidized area. Assessing the limitations of fluidized beds in this niche situation can prevent inefficiency in many applications. For example, in biomass gasification, the process of turning organic materials into hydrogen-rich synthetic gas, there may be moisture present in some parts of the biomass but not all (15). We found that after 0.4% water saturation, all water saturation levels resulted in a significantly decreased fluidized area. This result clearly supports our hypothesis because as soon as the bottom layer became wet, the top layer had significantly reduced in fluidized area. The results from the experiment showed that fluidization behavior changed as water saturation increased, transitioning from channeling, to partial, then to minimal, and finally exhibiting slugging.

We observed uniform fluidization from 0% to 0.4% water



Figure 5. Representative fluidized bed at 1% water saturation. 12.5 g of water was mixed with 1250 g of dry sand, and 1250 g of dry sand was layered on top of the mixture. 90 PSI of air was injected into the bed (18.5 cm by 21.0 cm). The large, encircled area in yellow shows the fluidized area captured by this photo (181.52 cm²). Other photos at this water saturation level captured fluidized areas of 192.09 cm² and 190.05 cm² and exhibited similar fluidized behavior (n=3).

saturation. The bottom layer at these water saturation levels can be classified as Group B particles and in the dry state since there were no visible clumps holding sand together, and they fluidized easily.

We begin to see a sharp decrease in fluidized area at 0.5% water saturation and observed clumps that held sand together, therefore falling into the criteria of the pendular state. This becomes a critical part of our analysis because being in any of Geldart's three states of water saturation (pendular, funicular, capillary) constitutes a grain as being wet. These results clearly support our hypothesis because as soon as the bottom layer becomes wet, the top layer has non-uniform fluidization. The observed trials that displayed minimal (30% to 50% water saturation), partial (0.9% to 20% water saturation), and channeling (0.5% to 0.8% water saturation) fluidization all fit within Group C. This matches the observed effect of water on particles seen in other experiments; water causes Group B particles (sand) to become Group C particles because the capillary forces act as the interparticle forces seen in Group C particles that resist fluidization (1,5). The observed channeling behavior from 0.5% to 0.8% water saturation indicates that the capillary bridges have not become cohesive all throughout the bottom layer, therefore allowing us to place these water saturation levels in the pendular state. The partial fluidization observed from 0.9% to 20% water saturation can then be marked as being in the funicular state, since the even reduction in fluidized area shows that the liquid bridges have become more uniform throughout the bottom layer. We can also observe visibly that fluidization is much weaker in intensity at these water saturation levels, since the air is fighting against much more forces and having a much

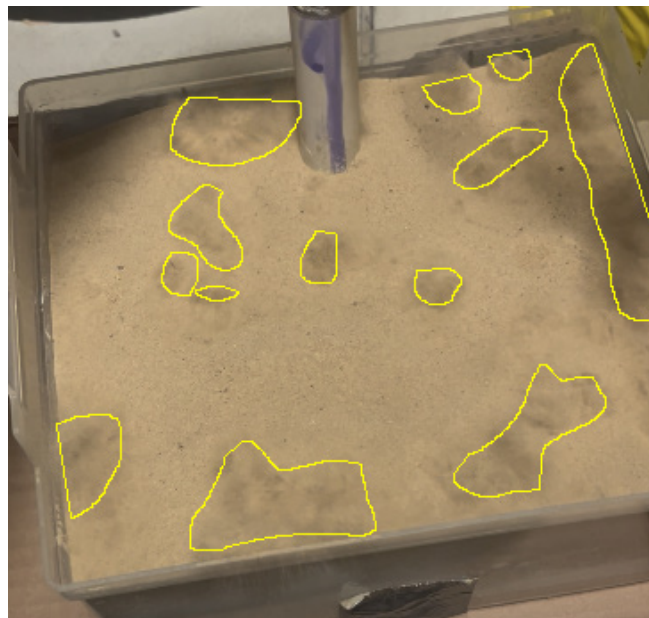


Figure 6. Representative fluidized bed at 30% water saturation. 375 g of water was mixed with 1250 g of dry sand, and 1250 g of dry sand was layered on top of the mixture. 90 PSI of air was injected into the bed (18.5 cm by 21.0 cm). The multiple areas encircled in yellow show the fluidized area captured by this photo (68.04 cm²). Other photos at this water saturation level captured fluidized areas of 68.46 cm² and 66.39 cm² and exhibited similar fluidized behavior (n=3).

harder time permeating through the bottom layer (8,13). Water saturation levels from 30% to 50% exhibited minimal fluidization with air escaping only at the very sides. Because we observed the bottom layer to be evenly saturated as a cohesive mixture, even closely resembling a slurry, we can connect these water saturation levels to the capillary state.

The 60% to 100% water saturation trials all exhibited slugging, which is typically associated with Group D particles. Still, because we observed only small sections where air escaped, these are Group C particles, not Group D particles. This observation matches with earlier works, which have observed that adding water to a mixture of Group A, B, or D alters their behavior to adopt that of Group C particles (5). The 60% to 100% water saturation levels can be considered to be in the slurry/saturated state, since we visibly observed that the bottom layer was a slurry, and slurries often exhibit slugging (1).

We were concerned about the introduction of mass into the system when water was added, but the results from our control experiment indicated that the addition of mass had minimal to no impact on our findings. Another concern was the increase in fluidization between the 0.5% and 2% water saturation levels. This could have been a result of inadequate mixing and distribution of the water, resulting in fluidization being channeled into the pockets where water was not present, and then later evening out as the water saturated the bottom layer more evenly.

There are multiple limitations and areas that our experiment failed to cover. We cannot accurately pinpoint a percent value that the mode of fluidization changes, especially for higher percentages of water saturation. Our trials at the



Figure 7. Representative fluidized bed at 60% water saturation. 750 g of water was mixed with 1250 g of dry sand, and 1250 g of dry sand was layered on top of the mixture. 90 PSI of air was injected into the bed (18.5 cm by 21.0 cm). The small yellow circles in the photo represent the fluidized area that exhibited slugging (10.19 cm²). Other photos at this water saturation level captured fluidized areas of 10.02 cm² and 11.14 cm² and exhibited similar fluidized behavior (n=3).

highest accuracy had intervals of 0.1%, but within that 0.1% could be the difference between being dry or entering the pendular state. Our biggest intervals showcase differences of 10% as the primary motivation behind our methods was to showcase a trend rather than an actual number. Therefore, we can approximate the threshold between modes of fluidization from our results, but our experimental testing structure causes that approximation to become increasingly inaccurate at higher water saturation levels. We also could not determine the pressure drop between the top and bottom layers, which could help us calculate the minimum fluidization velocity as water saturation increases. That could be a potential study that stems from our experiment: observe the minimum fluidization velocity as water saturation increases. The setup of our experiment has flaws as well: hole placement deviated from a straight line in the PVC network and the air compressor lacked a perfectly airtight seal, as we used duct tape to prevent any major air streams from coming out. An airtight seal would allow for more consistent results and, therefore, more reliable comparisons, since none of the air would leak out of the system. Air leakage can cause discrepancies in fluidization and alter our results. The presence of walls in our experiment may have resulted in friction between the sand and the container walls, creating a path of least resistance for the injected air to travel through. The introduction of friction into the system by these walls therefore redirects the fluidization to the sides of the bed where there is least resistance, because air always travels the path of least resistance (1). If the walls were eliminated or if they were entirely frictionless, it would result in less fluidization observed; gas bypassing would not occur and the air would be trapped underneath the sublayer, requiring passage through the bottom first. It is important to understand

how the presence of walls affects the flow pattern and the fluidization, but gas bypassing does not significantly affect our statistical analysis and our results.

Another interesting area to discover would be reversing the layers such that the top layer is wet and the bottom layer is dry. We tested this and observed that the bottom layer appeared to fluidize, and the top layer behaved as if there was no bottom layer. For example, a bed with water saturation of 30% did not fluidize at all, and adding a bottom layer did not change the behavior. We are not comfortable with drawing statistical conclusions on this version of the experiment because we were unable to fully observe the behavior of the bottom portion; we only saw the side of the bottom layer and not the top or bottom.

This experiment provides a different perspective on fluidized beds as it takes the unconventional approach of experimenting with spatial differences rather than changing the entire bed as a global variable. The results of this experiment show that having a wet sub-layer can severely decrease the effectiveness of fluidized beds, and that their utility is improbable because of their inefficiency in comparison to standard fluidized beds. All of the water saturation levels that resulted in beds in the pendular, funicular, capillary, or slurry state were associated with group C particles, which, by definition, are difficult to fluidize because their interparticle forces limit air flow. This directly supports our hypothesis because all those water saturation states mean that the bottom layer was wet, and they were linked with a decrease in fluidized area. Ultimately, there are many downsides to moisture in fluidized beds that will outweigh most benefits; the slugging caused by higher levels of saturation could potentially damage equipment and become more volatile in different circumstances.

MATERIALS AND METHODS

Preliminary testing

A fluidization bed was constructed by placing a PVC network, acting as the air inlet, into a 18.5 cm by 21.0 cm transparent container. A Task Force air compressor with a maximum of 125 PSI (2.2 standard cubic feet per minute (SCFM) at 90 PSI and 3.5 SCFM at 40 PSI) supplied air into the PVC network. The PVC network was comprised of three 0.5-inch PVC pipes (0.84-inch total diameter 0.602 inch inside diameter) with eighty-four 2.38-mm (diameter) holes, which had a 15 cm length and a 20 cm width (**Figure 8**). To determine the operating pressure that would be used during the experiment, the same fluidized bed setup was used to see the lowest possible PSI that would result in a fluidized bed. 2500 g of dry sand were used, occupying a total volume of 21.0 cm by 18.5 cm by 6.50 cm of height (including the PVC network), and the air pressure was increased from 20 PSI to 120 PSI by increments of 10 PSI in separate trials. It was observed that the lowest PSI that fluidization occurred at was 70 PSI, but fluidization also occurred at 80 PSI and 90 PSI. Anything above 100 PSI sprayed sand out of the container, which does not fit the criteria of fluidization (1). 90 PSI was determined to be our operating pressure because it was the strongest pressure that still matched the criteria of fluidization.

Hypothesis testing

1250 g of sand, exactly half of the total amount of sand, was weighed and put aside to be our dry sand. Trials were



Figure 8. Fluidized bed setup and bottom of PVC network. A polyvinyl chloride (PVC) network was placed in a transparent container, which received air from an air compressor. 84 holes with a 2.38 mm diameter were drilled on the bottom roughly 10 mm apart. The holes on the three main pipes on separate sides were 90 degrees apart from one another, and holes were drilled in a similar fashion on the curves of the PVC network.

based on varying levels of water saturation, which were defined by calculating a percentage of the weight (percent * 1250 g = mass of added water) and adding the respective amount of water to the mixture. Water saturation levels of 0% to 1% were tested in increments of 0.1%; 1% to 10% in increments of 1%; and 10% to 100% in increments of 10%. 1250 g of dry sand were mixed with the water according to the saturation percentage and layered into the fluidization bed, evenly covering the bottom and the PVC network so that all the sand was level on the bottom layer. 1250 g of dry sand was poured and evenly spread on top of the water saturated sublayer. The air compressor was allowed to accumulate as much air as it could hold until the pressure switch automatically turned on to prevent over pressurizing. The pressure regulator was adjusted to 90 PSI, as determined in our preliminary testing. While releasing air into the fluidized bed, photo documentation was taken to analyze results as soon as the bed displayed consistent behavior. How much fluidization occurred was also observed and was assigned a term based on the Geldart classification (5,6). We analyzed each photo using ImageJ to find the area that displayed fluidized behavior using the freehand selections. This area was divided by 388.5 cm², which was the total area of the fluidized bed, to calculate the percentage of area fluidized. The percent of area fluidized was plotted against the water saturation percent combined with the Geldart classification to produce the scatterplot. After the trial, all the sand was dried outside to ensure that no moisture was still left in the sand before we tested the next level of water saturation. The sand was checked for moisture by testing if it would fluidize, since wet grains alone do not fluidize (8). If it fluidized, the next amount of water was calculated, weighed, and added to 1250 g of sand to start the next trial. This process was repeated until all the water saturation levels were tested. All water saturation levels were tested three times.

Statistical analysis

We analyzed all results using an alpha level of 0.01 and assumed normality for all significance tests. We used a Welch's unpaired *t*-test because our tests at lower water saturation levels had much higher variance compared to our

tests at higher water saturation levels. All of the tests are independent because we dried the sand completely prior to each trial. We used *n*=3 as a practical number of trials and acknowledge that normality cannot be formally verified from the limited number of trials. However, given the large differences and effect sizes seen between our trials and 0% control, this limitation likely does not affect our conclusions. Using the estimated area obtained by the photo analysis from the ImageJ software, we used a two-sample Welch's unpaired *t*-test to compare two means on GraphPad to calculate the *t*-value and the *p*-value for each saturation level. All *t*-tests were compared to the 0% water saturation level results.

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