The impinging fluid can be used as a prevention of sedimentation in the flow of the pipe and the mixing process. Sedimentation is a problem that often occurs in fluid transportation and fluidization. Granular material behavior due to impinging is a phenomenon that is rarely studied. This condition is difficult to observe due to the position of complex fluid movements in the bed. The study tries to find the behavior of fluidization at various granular sizes. The effect of impinging into the granular bed has been observed with experimental studies. Hele-Shaw cell is used as equipment for the observation process. The glass sand is used as a medium of fluidization. The high-speed fluid is injected into a granular bed in a short time. Granular material moves because of the pressure impinging as fluidization. The motion of the granular material is observed by a camera to determine the behavior of the granular material. The primary outcome of the present study is the identification of two very distinct regimes. There are two types of post-impinging fluidization. The first type is the fluid cavity and fluidization. The condition starts with a fluid cavity expansion and continues with the fluidization process. The fluid cavity occurs because the fluid shock pressure pushes the granular material upward. Granular bonds hold the particles' connection and form a cavity. Fluidization after cavity expansion is a settling motion that is influenced by gravity, buoyancy, drag, and granular bonds. The other type is a local fluidized state. The limit for the occurrence of fluid cavity and fluidization is observed with the Reynolds number of impinging. The Reynolds number of impinging is calculated by the velocity of entry of the shock fluid in the granular and multiplied size of the particles divided by the viscosity. The fluid cavity post-impinging occurs at the Reynolds number of the impinging process less than 4,000 (laminar and transition flow area). The local fluidized state has Re of impinging more than 4,000, and the fluidization follows the flow and disappears immediately. This condition causes the bonding of the granules cannot maintain the agglomeration of the granules

Keywords: granular material, impinging, fluidization, fluid cavity, sedimentation, viscosity, drag force

UDC 66.096
DOI: 10.15587/1729-4061.2020.199035

AN EXPERIMENTAL STUDY OF FLUIDIZATION POST IMPINGING FLUID IN GRANULAR BED FOR BREAKING SEDIMENTATION

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Received date 23.06.2020
Accepted date 31.07.2020
Published date 31.08.2020

1. Introduction

Granular materials are widely used as raw materials and mixtures in many industries. It is a challenging task to study granular materials that have various particle sizes and shapes and properties. Granular material processing is estimated at around 10 billion metric tons every year in the world. More than three-quarters of granular raw materials are used in the chemical industry [1]. Many types of granular materials are used in various fields of industry. As the material used in large quantities in the handling, granules require a lot of energy to be processed. Granular processing needs special attention to save energy. Energy is needed for granular materials that handle 10 % of all energy produced for industry [1]. In the manufacturing industry, abrasive jet machining removes material using erosion and abrasion. The kinetic energy of the granule is related to its speed to cut the workpiece [2]. In mining, granules form as ore, gravel, and natural sand. Some researchers observe the pressure drop model of high-concentration graded particle transport in pipelines. The mechanism and influence of the particle size variation in different flow conditions [3]. The chemical and pharmaceutical industries use granular powder as a drug formula as a powder and pill. The mixing process was investigated to develop continuous pharmaceutical manufacturing [4]. The food industry uses rice, corn, soybeans, and other powder as raw materials. The structure of powder particles and powder concentrates is important to be observed related to the oxidation of food [5]. In energy production, granular coal is used as fuel for boilers. The particle size of coal in gas desorption varies with the absorbing gas and its working conditions [6].

Industry often uses granular material handling methods according to practical experience. This method causes the production process is not always optimal. Different characters of granular material cause low handling efficiency. Sedimentation is a problem in the flow of granular material. Sedimentation can be removed by stirring open channels, but it is difficult to do in closed channels. Impinging in granular material is one of the methods proposed in the prevention of sedimentation. Impinging is the process of injecting pressurized fluid quickly to create fluidization. The research investigates the effect of impinging fluid in granular. It is expected to find out the granular behavior in the bed post-impinging. The fluidization movements that occur are observed to be used as a basis for designing equipment to break down sedimentation. The character of the fluidization process is needed to determine the impinging time that must be done to get fluidization. Sedimentation can be removed easily when forming fluidization.

The study pays attention to previous research gaps in sediment breakdown methods. An instantaneous high-speed flow is injected vertically through the immersed granular material. In injection, the flow of crashing granular material is influenced by the granular drag force. Shock flow forms a fluid cavity in front of the nozzle. The study investigates the effect of the impinging shock flow in a granular bed. The investigation is done to obtain flow patterns, fluidization movement, and fluidization height. Granular size variations are used to observe the effect of granular properties on fluidization. Measurement of fluidization velocity is needed to indicate changes in fluidization. Fluidization forms always change, so that the pattern of movement is difficult to determine. The condition is observed to determine the limits of cavity fluid and fluidization after the impinging. Where the cavity and fluidization limits are determined to make the decision in the process of removing sediment.

2. Literature review and problem statement

Research on granular movements develops according to industry requirements. The researchers have been studying granular-granular and granular-fluid interaction. The flow of granular-fluid can be porous media or fluidized. Granular, as a porous medium at the pressure and speed of the liquid injected into the granular bed, does not cause fluidization. Granular material handling problems often occur in industrial processes. Sedimentation, as a form of grain, is one of the problems that occur in the pipeline.

The paper will present a fluidization phenomenon for granular material that may be used as a method for breaking up sedimentation. Several sedimentation cleaning methods are offered, but it often occurs in curved line pipes, long streams, and tanks.

The researcher observes the flow through the curve channel to know the process of sedimentation and erosion. Flow and sedimentation are related to the time scale of this event, the effect of flow rates, and granular particle size [7]. Sediment shocking is proposed in the flushing process. Shocking fluid with large flow and pressure in the pipeline is used to prevent sedimentation [8]. The other research discusses flushing with the pulse method. The results of this research show that there are savings in the water used in the flashing pulses process [9]. Studies about the jet impact for sediment are developed to get better proses. They developed the experiment effect of jet characteristics nozzle diameter, jet velocity, and jet discharge [10]. Researchers use many methods to get fluidization. The fluid jet is shot to the granular form and immersed location to break the granular. The jet produces an upward push and changes the granular arrangement [11, 12].

The experiments inject liquid into the granular bed to observe the behavior of fluidization. Local fluidization is caused by the liquid flow being unable to move the granular perfectly. When the velocity of the fluid is increased, granular is moved on the orifice's contact hole. Fluidization is bounded by a layer of particles moving in a static granular bed. Local fluidization was difficult to observe because of the complex fluid-granular motion in the bed. Local fluidization causes material movement and arrangement of granular piles [13, 14]. Perfect fluidization is fluidized to reach the surface of granular. A local fluidization pattern above the reservoir when granular are injected with low discharge. Fluidization expands into a large when the fluid flow is increased. The motion forms a fluidization chimney when it reaches the top of the bed. The fluid velocity influences the chimney diameter [15, 16].

The ability of fluid to penetrate is affected by porosity and granular size. Porosity is one of the crucial factors that have a considerable impact on structure and performance. Because of the complex composition, it is hard to observe the porosity without the help of lab experiments [17]. In fine grains, the narrow gap between fine granular produces high resistance of the fluid. The relationship between fine particles binds to each other because of the granular bond. The relation between grains is influenced by cohesive forces. The cohesive force can be expressed by the number of granular bonds (B_o). The ratio between the maximum tensile force and the average force because of external compression [18]. The presence of granular bonds in fine grains reduces the ability of fluidization in granular beds.

From the many research conducted, there are unresolved issues related to handling granular sedimentation. The objective difficulty associated with granular handling is the different nature of each granular character. Empirical research is often done to handle cases. Empirical research in the industry is not useful because it requires high costs. The way to overcome this condition is the granular behavior approach. Fluid impinging in granular material is one phenomenon that has not been discussed in detail. It can be proposed as the prevention of sedimentation in the pipeline flow. It is necessary for studies on the impact of granular materials when exposed to fluid impact. The experiment is done to study the effect of the impact of impinging in an immersed granular fluid bed.

3. The aim and objectives of the study

The aim of this study is to investigate fluidization movements. The study investigates impinging fluid in immersed granular.

To achieve the aim, the following objectives have been set:

– to study the effect of granular diameter on post-impinging fluidization time carried out in immersed granular bed;

– to study the effect of pressure on differences in the diameter of the granular material carried out for the impinging fluid in a granular bed;

– to study the form of granular fluidization as a result of impinging fluid in a granular bed.

4. Materials and methods of research

The fluid-granular bed particle interaction was observed in a Hele-Shaw cell arranged as in Fig. 1. The dimension of the Hele-Shaw cell is 200×180×3 mm. Water was impinging into the granular bed through the bottom side of the Hele-Shaw cell with a nozzle diameter of 1 mm. The inlet of impinging is equipped with a control valve, which is connected to the timer. Two valves were installed in the fluid line to regulate the water pressure into the Hele-Shaw cell. The water was injected to the granular bed in the Hele-Shaw cell at a pressure varied as 0.5 kg/cm^2, 1.0 kg/cm^2, 1.5 kg/cm^2, 2.0 kg/cm^2, 2.5 kg/cm^2 and 3.0 kg/cm^2 for 0.1 s. The pressure is measured by a pressure gauge installed close to the inlet of the Hele-Shaw cell.

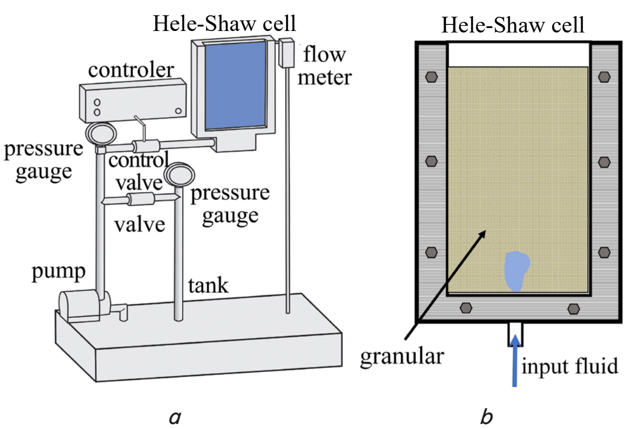


Fig. 1. Equipment for observation of fluidization: *a* – arrangement of equipment; *b* – Hele-Shaw cell

Particles bed in the Hele-Shaw cell was granular material made of glasses. The diameter of granular material was 80 μm, 100 μm, 140 μm, 230 μm, 290 μm, and 340 μm having densities of 2600 kg/m^3. The granular diameters were used to represent several sizes, namely very-fine sand 63–125 μm, fine sand 125–250 μm, and medium sand 250–500 μm [19].

A granular form of glass particles was also observed with the Dino-Lite digital microscope, as seen in Fig. 2.

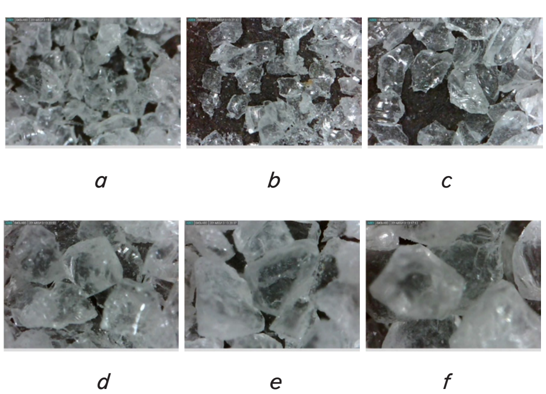


Fig. 2. Granular materials for the experiment: *a* – 80 μm; *b* – 100 μm; *c* – 140 μm; *d* – 230 μm; *e* – 290 μm; *f* – 340 μm

The particles were illuminated with multiple light colors for fluidization motion visualization. The fluidization motion patterns were captured by a video camera at a rate of 50 frames per second. The video was extracted into JPG format with Video to JPG Converter build 1228 V.504.

5. Results of investigation of impinging effect in a granular bed

Impinging fluid into granular has two behavior models, i. e., porous media as fix granular and movement fluidized. The step of fluidization granular is started by cavity forming and continued with fluidization. The pattern of fluidization depends on the diameter of the granular material and pressure. Granular diameters are grouped based on fluidization behavior and settling motion. Variation of diameters during impinging causes three different behaviors, fluidized in very fine granular, fine granular, and medium granular.

5. 1. Impinging in very-fine granular

Impinging in very fine granular (80 μm) results in the formation of the cavity and continued with the slow motion of fluidization. The cavity formation process takes place very rapidly, along with the impact of fluid into the bed. The granular start fluidized motion after completion cavity formed. The fluidization process occurs due to the descending movement of granular at the upper side of the hollow. Visualization of cavity formation and granular fluidization of diameter 80 μm is shown in Fig. 3.

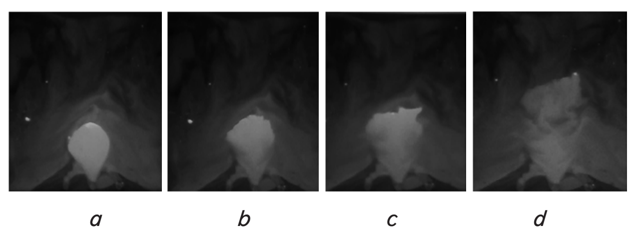
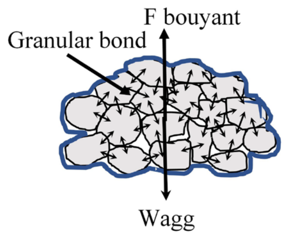
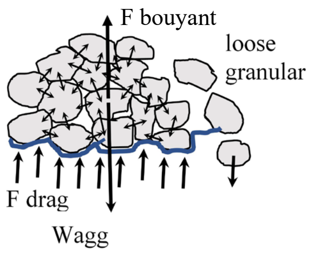


Fig. 3. Movement of 80 μm granular by impinging for 0.1 s at a pressure of 2.0 kg/cm^2 into the granular bed: *a* – 0.5 s; *b* – 10 s; *c* – 20 s; *d* – 23 s

Post-impinging, fluidization is very slow. Fig. 3, *a* is the formation of a fluid cavity. The fluidization motion is continued by Fig. 3, *b*–*d*. Movement fluidization is a settling motion of granular agglomerate loose from the arrangement. Movement slows settling due to particles no easily separated from the group. Very-fine granular has a granular bond that affects binding between individual particles. The intensity of the cohesive strength can be measured with granular Bond Number (B_{og}). It is the ratio between the maximum tensile force and average power for external compression of the particle's mass. Granular Bond Number is expressed by $B_{og}=F_{cohesion}/W_g$. The variable $F_{cohesion}$ is cohesive forces between granular particles and W_g, is the weight of the granular particles. If the value B_{og}>>1, then the connective force between granular is dominant. So that the particles bind with each other, the influence of bonding particles causes settling agglomerate granular. Granular agglomerates settle when the cohesive forces are less than agglomerate mass. A moment granular agglomerate separated from the main granular, the force acting on the granular is cohesive force $F_{cohesion}$, gravity W_g and buoyancy forces F_B.



a



b

Fig. 4. Forces are acting on granular agglomerate: *a* – granular agglomerate; *b* – drag force breaking the bonds

Fig. 4 shows that the cohesive forces maintain an agglomerate from being destroyed. Cohesive forces make the bond between the particles to maintain the arrangement. The forces that work form a bond between the granular are

$$F_{cohesi} = F_{vdw} + F_{cap} + F_{asp}. \quad (1)$$

The force of the Van Der Walls bonding, F_{vdw}, is an attractive force between molecules or between group entities in the entity. It is caused by molecular bonding or electrostatic interactions of ions or ionic groups or neutral molecules. Capillarity force F_{cap} is the force that is formed by the surface tension, which is owned by the working fluid in granular. Contact force F_{asp}, is a bond force related to the particle surface roughness, particle diameter, d_p, and surface roughness characteristics d_{asp}.

The buoyant force maintains granular agglomerate to stay and avoid settling. Buoyant force equations for granular agglomerate are expressed by

$$F_{Bag} = \left(\rho_{ag} - \rho_{fluid}\right) g \cdot V_{ag}, \quad (2)$$

where F_{Bag} is the buoyancy of the granular agglomerate, ρ_{ag} is the density of the granular agglomerate, ρ_{fluid} is the fluid density, g is the gravity, and V_{ag} is the granular agglomerate volume. The agglomerate settles when the buoyant force and bonding force are less than the agglomerate weight. Fluidized motion in fine granular is very slow because of the density of granular agglomerate much less than individually. Granular agglomerate density ρ_{ag} is the density granular porosity. The settling movements cause the drag force F_D. The drag force is expressed by

$$F_D = \frac{1}{2}\left(C_D \cdot \rho_f \cdot U_r \cdot A_p\right), \quad (3)$$

where C_D, U_r, and A_p is the drag coefficient, settling velocity, and granular agglomerate cross-section. Settling velocity is a function of the drag coefficient and Reynolds number [20]. Because the fluid velocity at the time of settling is equal to 0, the Drag coefficient is expressed by the equation

$$C_D = \frac{24}{R_e}, \quad (4)$$

$$R_e = \frac{\rho_f U_s d_p}{\mu}, \quad (5)$$

where ρ_f is the fluid density, d_p is the particle diameter, and U_s is the fluid velocity. When the outside forces are greater than the cohesive forces of particles, granular agglomerates are crushed to form grains. Fig. 4, *a* explains how granular agglomerate becomes a strong bond. Fig. 4, *b* explains that the cohesive force is smaller than the external force causing agglomerate granular rupture. The fluidization moves perfectly when the bonds between the particles are released.

The fluidization of the granular material shows the change of formation from the impinging process. The velocity of movement of 80 μm granular material due to impinging can be seen in Fig. 5. The graph describes the occurrence of two conditions, namely the formation of fluid cavities and settling fluidization. Pressure variations are given to show the effect of fluid cavity motion and settling fluidization. The graph shows that fluidization has the same acceleration.

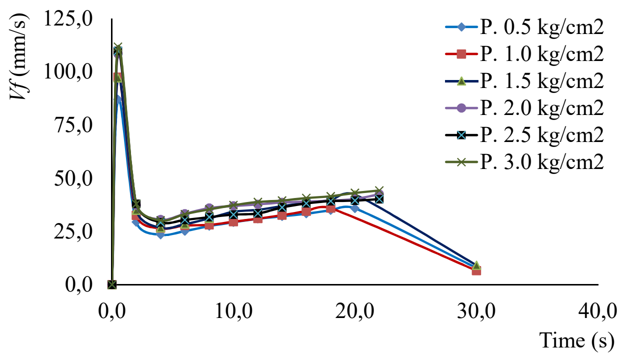
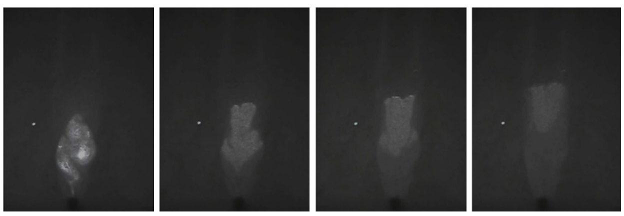


Fig. 5. Fluidized movement (V_f) at the diameter of granular 80 μm

The time of fluidization in very fine granules can be seen in Fig. 5. From the graph, it can be explained that impinging is a process of fluid expansion into the granular. Granular beds undergo fluid cavity formation. The movement to form a fluid cavity occurs very quickly (100 mm/s). After the granular impinging is stopped for a moment and continued with fluidization. The fluidizing motion is slower compared to the expansion of the fluid cavity. Fluidization movements are influenced by loose granular bonds and buoyancy. The fluidization movement takes place at a speed of around 25 mm/s. Fluidization movements accelerate because of the release capability of the agglomerates, the more the speed of the very fine granular fluidization is almost the same at each pressure. This shows that pressure has little effect on very fine granular.

5. 2. Impinging in fine granular

Granular material with a size of 100 to 300 μm is the size of fine sand, so the granular behavior is different from very fine granular. Fluidization of fine-granular size granular moves faster than a very-fine-granular size. The influence of the cohesive forces in granular decreases when the diameter is greater than 100 μm [21]. From the experiments, it can be seen that the motion of fluidized granular of 100 μm in diameter has different configuration fluidization with 80 μm fine granular. The motion of fluidized granular of 100 μm in diameter is faster than with a diameter of 80 μm. In the fine sand diameter, the motion of fluidization run individually granular. The granular is influenced by the process of the fluidized granular bond. Granular bond causes the grain into resistance settling and forming fingering fluidization. Fig. 6, *a* is a post impinging cavity and Fig. 6, *b*, *c* are fingering patterns formed in the fluidization. Fig. 6, *d* is a fluidization stop after setting the process. Fluidization moves up after the impinging forces are gone due to unstable conditions on the granular material. Gravity has a greater value than the buoyancy and drag forces.



a *b* *c* *d*

Fig. 6. Movement of 100 μm granular by impinging for 0.1 s with a pressure of 2.0 kg/cm^2 into the granular bed: *a* – 0.5 s; *b* – 1.0 s; *c* – 7.5 s; *d* – 12 s

The fluidization of 100 μm granular material differs in movement compared to 80 μm. Post impinging, granular has short-term motion. Fluid cavities move quickly. The graph describes the occurrence of two conditions, namely the formation of the fluid cavity and settling fluidization. The velocity of 100 μm fluidization granular is shown in Fig. 7.

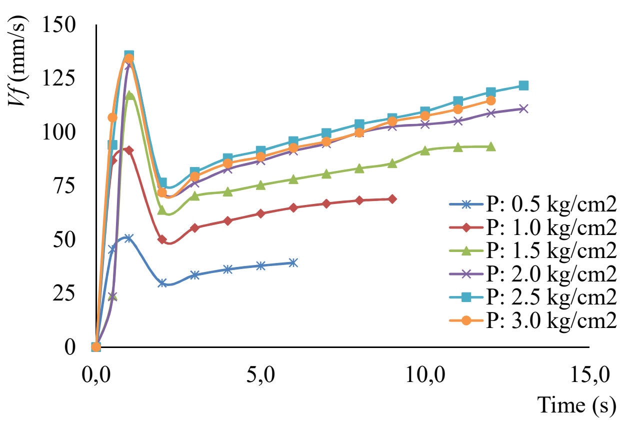
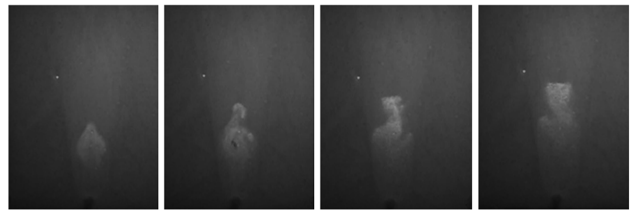


Fig. 7. Fluidized movement (V_f) at the diameter of granular 100 μm

Fig. 7 shows a cavity expansion followed by settling as a fluidization process. The cavity expansion at a grain diameter of 100 μm is lower than at a grain diameter of 80 μm, so it shows that the granular bond at a diameter of 100 μm is lower than the 80 μm grain. The deposition process occurs faster because the grain mass is heavy. The velocity fluid to make a fluid cavity at 0.5 s is 13.5 mm/s for P 30 kg/cm^2. The fluid cavity is followed by settling fluidization. The average time for the fluidization process is 12 s.

Fig. 8 is the result of impinging on a granular diameter of 140 μm. In this condition, the effect of granular bond is very low, so the form of fingering is greater. Fluidization moves faster than smaller granular. Fingering is observable because of the influence of a weak granular bond.



a *b* *c* *d*

Fig. 8. Movement of 140 μm granular by impinging for 0.1 s with a pressure of 2.0 kg/cm^2 into the granular bed: *a* – 1.0 s; *b* – 1.5 s; *c* – 2.0 s; *d* – 4.0 s

The size of the granules influences the time of the fluidization process. Coarse granular is used in the observation, resulting in shorter fluidization. In impinging 0.1 s with a pressure varying between 0.5 up and 3.0 kg/cm^2, granular diameter changes affect the settling time. In Fig. 9, it can be observed that the impinging 0.1 s at a pressure of 3.0 kg/cm^2 can move 200 mm/s for cavity expansion and granular fluidization 300 mm/s. The height of the cavity and the height of fluidizing are decreased at low pressures. The pressure in the process of impinging influences the height of the cavity.

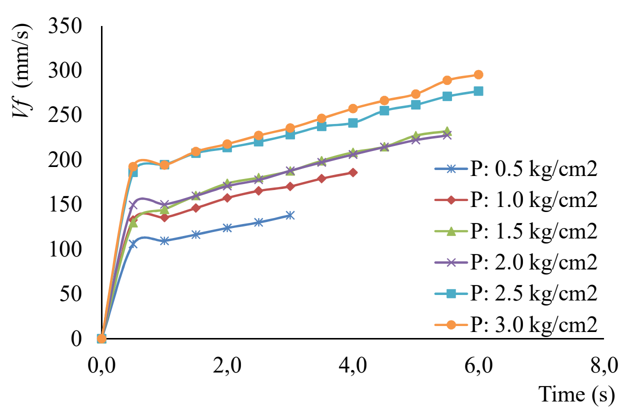
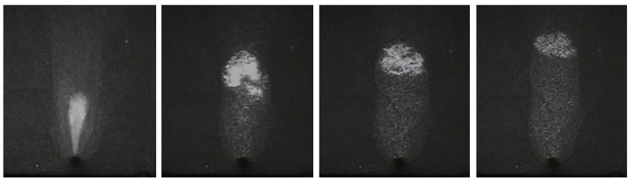


Fig. 9. Fluidized movement (V_f) at the diameter of granular 140 μm

Fig. 10 shows that the impinging 0.1 s and 2.0 kg/cm^2 with a 230 μm diameter granular is not fingering in fluidization. The effect of the granular bond is weak in this condition. Granular settling does not bind to each other. Granular moving individually to follow the movement of impact flow when given the impact load. Post impinging, granular material undergoes settling individual granular. The settling process increases the granular velocity because the granular bond does not inhibit the process of settling.

Granular size affects the form of the graph of the velocity motion of fluidization. Fig. 11 shows the fluidization motion of the 230 μm granular. The graph describes the occurrence of settling fluidization conditions. Pressure variations are given to test the effect of fluidization. The graph does not show the formation of fluid cavities.



a *b* *c* *d*

Fig. 10. Visualization of motion of 230 μm granular by impinged 0.1 s with a pressure of 2.0 kg/cm^2 into the granular bed: *a* – 0.3 s; *b* – 0.9 s; *c* – 1.5 s; *d* – 2.5 s

Settling time in post-impinging granular diameter 230 μm, can be seen in Fig. 11. The velocity of settling on granular material 230 μm is shorter than the granular with a smaller diameter. The graph also explains that the time needed for the fluidization process is around 3 s. The movements that occur are very fast, particles are not affected by granular bonds when impinging starts, the drag force of the fluid flow pushes the granular grain. Some fluid escapes through the gap between the particles. Granular 230 μm has a large gap to pass through the fluid. Post-impinging, the granular is immediately stable and rearranges its structure.

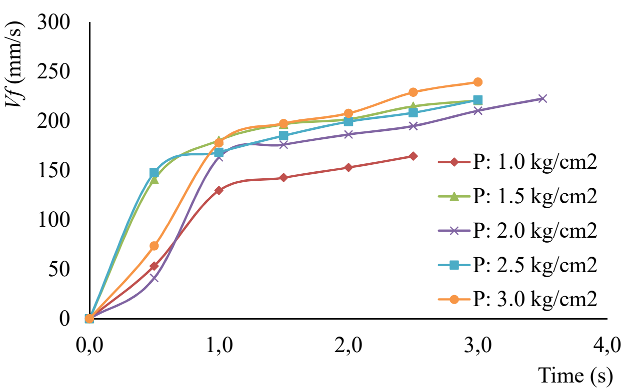


Fig. 11. Fluidized movement (V_f) at the diameter of granular 230 μm

5. 3. Impinging in medium granular

The particle size of the sand medium starts from 250 μm to 500 μm. The experiments with 290 and 340 μm diameters of granular describe the medium-sand granular movement, and fluid flows through the slits granular material. Impinging at 290 μm with a pressure of 3.0 kg/cm^2 shows a small influence on the change in granular arrangements. The time of granular deformation, at the end of the nozzle hole, is about 1 s. At low pressures, the composition of grain is fixed, which means no deformation or granular motion. The quality of fluidization depends on the bed geometry, the medium properties, and the fluid flow rate. The minimum velocity for the fluidization of particles increases with an increase in the density of fluidization [22].

In the medium sand type, the post-impinging the fluid flows briefly at high velocity. In large sizes, granular is not fluidized. Fluid infiltrates in the gap between the granular. These conditions create a turbulent flow in the granular bed. Forchheimer develops the Darcy equation to resolve the turbulent conditions by adding mass of fluid ρ_f and β inertia factor into the Darcy equation.

$$\frac{dP}{dL}=\frac{\mu}{k}\cdot U_f+\rho_f\beta\cdot U_f^2, \qquad (6)$$

where U_f is the velocity of the flow on the sidelines of granular particles, k is the permeability of the medium, μ is the fluid viscosity, L is the length of the porous medium, and P is the fluid pressure [23]. When the pressure is increased, the turbulent flow enters the bed quickly. However, the mass flow is unable to push the granular composition. The graph of the velocity of fluidization and deformation of granular can be observed in Fig. 12.

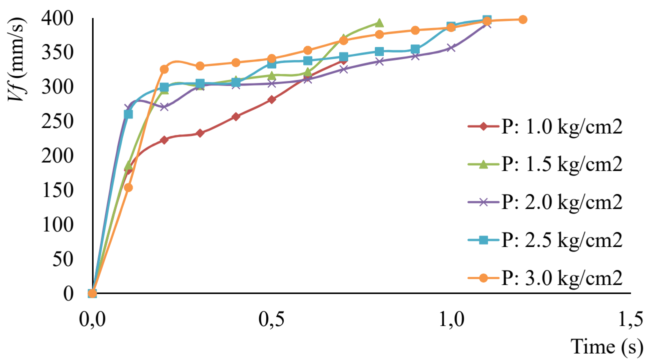


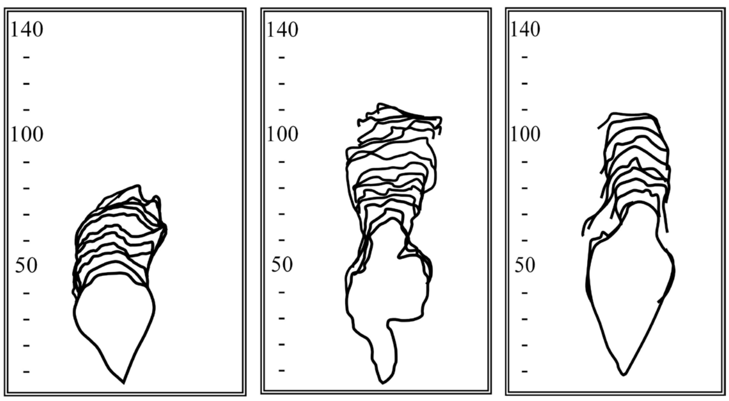
Fig. 12. Fluidized movement (V_f) at the diameter of granular 290 μm

Fig. 12 shows a graph of fluid motion that moves up without a cavity expansion. Granular fluidization moves quickly and disappears immediately. Fluid flow directly penetrates the granular bed and escapes out of the granular bed. Fluidization occurs very quickly and disappears. The average fluidization velocity is around 1 s.

5. 4. Patterns of granular motion

The size of the granular material determines the pattern of the movement of the granular material. Post-impinging, very fine granular material forms a wide cavity fluid. The granular bond between the granules and the shear thickening keeps the granules from moving upward. The large particle size causes the effect of granular bonds to be low, and the mass of particles to be great. This condition affects the ability of fluidization and settling post-impinging. Fig. 13 explains that impinging on an 80 μm granular area produces a wide fluid cavity. At larger sizes (Fig. 13, *b*, *c*), impinging succeeds in forming a deeper cavity, but the pattern of movement goes faster. Fluidization moves even faster than large particle sizes. For large particles (290 μm), the ability of fluidization to move will disappear, as shown in Fig. 12.

The height of the post-impinging granular material motion is important to be discussed because it is needed to determine the ability to solve the depositional case. In observation, the height of the granular motion is influenced by the ability to escape from the granular bond and the ability to settle. In very-fine granular, the ability of granular bonds to bind to the material is very strong. So the fluidization lasts for a long time, but the fluidization motion cannot be high. Fig. 14 shows that at a granular size of 80 μm, the height of fluidization is around 80 mm in a granular bed. In fine granular, the ability of fluidization develops very well. The weak inter-granular bonding force makes it easy for granular material to move more easily. When the shock flow is inserted into the granular bed, the granular immediately moves to follow the flow. The fluid movement would push the granular and continued settling motion. Settling movements occur faster (approximately 5–12 s), and the height of fluidization develops to around 140 mm. In larger granular (granular medium), the ability of granular fluidization will decrease. This condition occurs because the property of the granular material becomes porous media. A 290 mm granular height indicates a fluidization height of less than 40 mm and disappears immediately.



a *b* *c*

Fig. 13. Patterns of granular motion by impinging for 0.1 s with a pressure of 2.0 kg/cm^2: *a* – 80 μm; *b* – 100 μm; *c* –140 μm

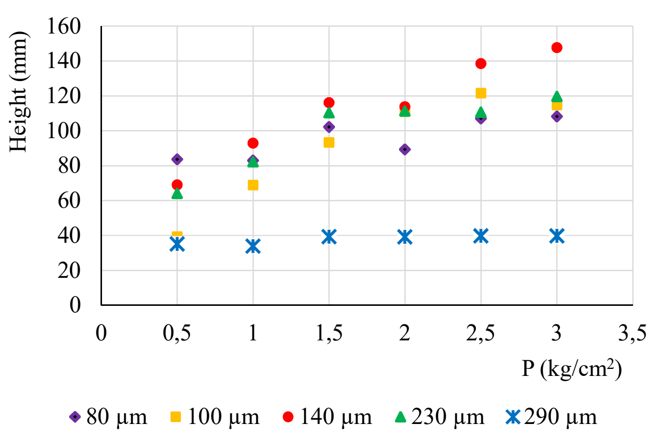


Fig. 14. Height of fluidization at post-impinging vs impinging pressure

The minimum velocity of the fluid is needed, which passes through the granular material to form fluidization. The value of buoyancy approximates the minimum velocity on the granular porosity and with pressure. Fig. 14 explains the effect of impinging pressure on the fluidization height of granular material. In large granular materials, the effect of pressure on fluidization is very low. It happens because the fluid, which is impinged flows easily through the particle gap. Fine granular material has gaps between particles that are more difficult to penetrate. This causes the formation of fluid cavities and continues with the process of fluidization in the form of material settling.

5. 5. Boundary of the cavity and fully fluidization

The observations prove that the time of movement of granular fluidization has a relationship with the diameter and velocity of fluid flow. To determine the effect of different granular sizes, the approach of Reynolds number of impinging (R_e^*) is used:

$$R_e^* = \frac{\rho_f U_f d_p}{\mu}, \quad (7)$$

where ρ_f is the fluid density, d_p is the particle diameter, and U_f is the velocity of fluid inlet granular bed, and μ_d is dynamic viscosity. The incoming fluid velocity is expressed by the debit (Q) getaway that passes through the granular bed divided by the impinging time (0.1 s).

Fig. 15 shows the motion times of fluidization observed at different Re* with diameter variation. The smaller particle diameter causes the large cavity and results in longer settling time. The large particles were going to mix with water in the direction of flow. Fig. 15 explains that the Reynolds number of impinging velocity results in a region of cavity expansion of less than 4,000. This value is the boundary of laminar and transition flow. Region of fluidization without cavity expansion occurs at the Reynolds number of impinging velocity above 4,000. The impinging process in the area results in short fluidization and porous media condition.

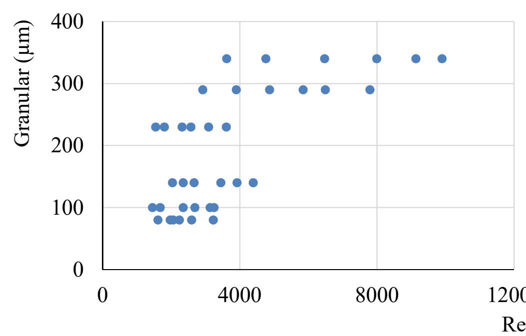


Fig. 15. Reynolds number on differences in granular diameter at impinging 0.1 s

The fluidization of movement can be made a regional breakdown of the difference in behavior. In fine granular, the granular effect bond is very strong, so the fluidization begins with settling agglomerate granular. Strong granular bonding is shown from the number of the granular bond B_{og} much greater than 1. When B_{og} is close to 1, the bond was not strong enough to hold granular. Movement of settling fluidized has happened right away was caused by the influence of poor bond of granular. The condition affects the shape of fingering fluidization.

The effect of granular bond is lost at a large granular diameter. The mass of granular, which is larger than bond cohesion, caused the material to move down immediately after forming the cavity. In these conditions, the down movement patterns do not result in fingering. Impinging process fluid with a larger diameter (340 μm) resulted in porous media behavior. Flow-through granular bed directly, so flow out bed rapidly.

6. Discussion of the results of studying the effect of impinging in a granular bed

Impinging is used to push the granular material and get fluidization. The sizes of granular will find out the fluidization patterns. The results of the experiment stated that different granular sizes cause different times and high fluidization. Impinging in very-fine granular cause fluid cavity is formed immediately, then granular agglomerates move down and break into fluidization. The figure explains that fluid cavities are formed spontaneously with a large impact force. In the process of impinging, the formation of fluid cavities 110 m/s^2 (Fig. 5) and the acceleration of formation up to 140 m/s^2 are observed (Fig. 7). High acceleration indicates a large force to move the granular mass. Where the force is a time of acceleration of motion. The very-fine granular has long time fluidization. The ability of fluidization in very fine granular is affected by granular bonds. Granular bonds prevent spontaneous fluidization due to impinging. Fluid thrust on granular material forms cavity fluid. Granular bonds occur in very fine grain sizes. Granular bonding decreases in large grains. The relationship of granular size with granular bonds is expressed by the relationship between the ratio of maximum tensile strength and the average power for external compression of the mass of the particle. The ability to bond between grains is based on the cohesive force between granular particles and the weight of granular particles. The larger the grain size, the shorter the fluidization time. This condition can be observed in Fig. 9, 11. That is because granular bonds do not have strong bonds that can hold the connection between granular during fluidization.

Post impinging granular behavior can be used as data on material properties. The data can be used as a basis for designing system breaking sedimentation. The upward movement of instability is shown by visualizing the fluidization movement shown in Fig. 3, 6, 8. The granular behavior can be observed and selected methods of solving the sediment problem base on the characteristics. Impinging is an alternative method for removing granular material besides the mechanical and flushing methods. Mechanical methods cannot be used in turning channels. The flushing method requires high pressure in the process of granular breakdown. The impinging process with a controlled pressure results in a measured fluidization area. In the research, nozzles installed on the bottom of the bed to produce fluidization movements are used. It is a disadvantage of the impinging-immersed method because it is necessary to build a piping system for impinging in the breaking granular. The process is also limited by the material of granular.

Differences in granular properties cause this research limited in the type of granular used in the experiment. Research is needed with different materials to get to produce the condition of the granular material handled. Several characteristics must be considered about granular material. In very fine granular material that has an influence on the bonding forces between particles, the gap between narrow particles that causes fluid cannot flow easily between particles. This condition bonds between particles to form a large resistance to the fluid. Fluid strongly pushes granular material, but granular material has thickening shear to hold fluid. In experimental results, particles of 80 μm can make fluid cavities for a long time, the larger granular particles will settle and stop fluidizing. In larger granular materials, resistance decreases because there is no inter-bonding force. After impinging, the formed fluid cavity is also filled with granular fluid carried by the flow. So that fluidization occurs from the beginning of the impinging process and does not enlarge.

The effect of fluidization properties on changes in granular size is an interesting finding. This phenomenon can be proposed in the design of equipment developed. The design needs to consider the working conditions of the system. Equipment follows the material properties to be handled. Limited information on granular properties is a problem in industrial applications. Some changes need to be prepared to research in the industry. The dimensions of the equipment in the factory are also different behavior. This fact is a challenge for researchers to study granular motion in industrial applications with different variable dimensions.

7. Conclusions

1. Fluidization processes are due to the flow that breaks down the granular material's composition following the flow of the fluid. At the time of fluid flow is stopped suddenly, granular material has a deposition process. The size of the granular material affects the fluidization process. Very fine granular has a composition of particles with strong bonds. Interference between particles does not break bonds and granular move in the form of the agglomerate. So the depositional fluidization process will take a long time. Large granular materials do not have bonds between dominant particles, so the process of fluidization is not influenced by bonds between particles.

2. The effect of pressure during the impinging process is the height of the granular material's fluid cavity. The higher the impinging pressure, the greater the fluid cavity in the granular material. This causes a large pressure producing a higher force to develop a fluid cavity. The effect of pressure is not significant on the rough granular material. Large gaps between the particles cause the impinging fluid to easily escape so that the pressure cannot apply force to the particle cross-section plane.

3. The form of fluidization post impinging is determined by the size of the granular material. In very-fine granular material, post-impinging fluidization begins with a fluid cavity formation and is followed by long-lasting fluidization. Agglomerates of granular material move down and break into granules of fluidization. Fine granular material has a form of fluidization that occurs immediately after the formation of a fluid cavity. Granular material will immediately fluidize without the formation of fluid cavities. To determine the area of the occurrence is the fluid cavity and fluidization approached by the Reynold Number. Granular motion is divided into two zones, which have different properties. Region 1 is fluidization with cavity expansion ($Re<4,000$). The motion is influenced by the granular bonds. Granular agglomerates move and are broken because of the drag force. Region 2 is fully fluidization granular ($Re>4,000$). In this region, motions of fluidization are not influenced by granular bond, and the granular bond is negligible.

References

1. Amen'abar, I. M. F. (2009). Exploring Analogies Between Granular Materials And Fluids. University of Pittsburgh. Available at: http://d-scholarship.pitt.edu/9438/1/Figueroa_Isabel_2009_6.pdf
2. Melentiev, R., Fang, F. (2019). Theoretical study on particle velocity in micro-abrasive jet machining. Powder Technology, 344, 121–132. doi: https://doi.org/10.1016/j.powtec.2018.12.003
3. Miedema, S. A. (2016). The heterogeneous to homogeneous transition for slurry flow in pipes. Ocean Engineering, 123, 422–431. doi: https://doi.org/10.1016/j.oceaneng.2016.07.031
4. Tomita, Y., Nagato, T., Takeuchi, Y., Takeuchi, H. (2020). Control of residence time of pharmaceutical powder in a continuous mixer with impeller and scraper. International Journal of Pharmaceutics, 586, 119520. doi: https://doi.org/10.1016/j.ijpharm.2020.119520
5. Haas, K., Obernberger, J., Zehetner, E., Kiesslich, A., Volkert, M., Jaeger, H. (2019). Impact of powder particle structure on the oxidation stability and color of encapsulated crystalline and emulsified carotenoids in carrot concentrate powders. Journal of Food Engineering, 263, 398–408. doi: https://doi.org/10.1016/j.jfoodeng.2019.07.025
6. Zhao, W., Wang, K., Cheng, Y., Liu, S., Fan, L. (2020). Evolution of gas transport pattern with the variation of coal particle size: Kinetic model and experiments. Powder Technology, 367, 336–346. doi: https://doi.org/10.1016/j.powtec.2020.03.061
7. Duarte, C. F., Nadim, N., Chandratilleke, T. T. (2019). Experimental study of granular bed erosion and sedimentation subjugated to the secondary flow structures in curved ducts. Advances in Mechanical Engineering, 11 (11), 168781401988525. doi: https://doi.org/10.1177/1687814019885255
8. Hyun, I.-H., Cheon, S., Kim, D., Seck, D., Choi, S. (2014). Improvement of Fire Hydrant Design to Enhance Water Main Flushing. Procedia Engineering, 70, 857–863. doi: https://doi.org/10.1016/j.proeng.2014.02.094
9. Tang, Z., Wu, W., Han, X., Zhao, M. (2017). An Experimental Study of Two-Phase Pulse Flushing Technology in Water Distribution Systems. Water, 9 (12), 927. doi: https://doi.org/10.3390/w9120927
10. Lakusic, S. (2018). Physical model study for evaluation of jet impact on sediment flushing. Journal of the Croatian Association of Civil Engineers, 70 (09), 811–818. doi: https://doi.org/10.14256/jce.1499.2015
11. Fan, W., Bao, W., Cai, Y., Xiao, C., Zhang, Z., Pan, Y. et. al. (2020). Experimental Study on the Effects of a Vertical Jet Impinging on Soft Bottom Sediments. Sustainability, 12 (9), 3775. doi: https://doi.org/10.3390/su12093775
12. Thaha, M. A., Triatmadja, R., Yuwono, N., Nizam, N. (2018). Minimum Jet Velocity for Unbounded Domain Fluidization as a New Dredging Methods. Engineering Journal, 22 (5), 1–11. doi: https://doi.org/10.4186/ej.2018.22.5.1
13. Philippe, P., Badiane, M. (2013). Localized fluidization in a granular medium. Physical Review E, 87 (4). doi: https://doi.org/10.1103/physreve.87.042206
14. Zoueshtiagh, F., Merlen, A. (2007). Effect of a vertically flowing water jet underneath a granular bed. Physical Review E, 75 (5). doi: https://doi.org/10.1103/physreve.75.056313
15. Alsaydalani, M. O. A., Clayton, C. R. I. (2014). Internal Fluidization in Granular Soils. Journal of Geotechnical and Geoenvironmental Engineering, 140 (3), 04013024. doi: https://doi.org/10.1061/(asce)gt.1943-5606.0001039
16. Montellà, E. P., Toraldo, M., Chareyre, B., Sibille, L. (2016). Localized fluidization in granular materials: Theoretical and numerical study. Physical Review E, 94 (5). doi: https://doi.org/10.1103/physreve.94.052905
17. Liu, Y., Li, M., Su, P., Ma, B., You, Z. (2020). Porosity Prediction of Granular Materials through Discrete Element Method and Back Propagation Neural Network Algorithm. Applied Sciences, 10 (5), 1693. doi: https://doi.org/10.3390/app10051693
18. Singh, A., Magnanimo, V., Saitoh, K., Luding, S. (2014). Effect of cohesion on shear banding in quasistatic granular materials. Physical Review E, 90 (2). doi: https://doi.org/10.1103/physreve.90.022202
19. Blott, S. J., Pye, K. (2012). Particle size scales and classification of sediment types based on particle size distributions: Review and recommended procedures. Sedimentology, 59 (7), 2071–2096. doi: https://doi.org/10.1111/j.1365-3091.2012.01335.x
20. Betancourt, F., Concha, F., Uribe, L. (2015). Settling velocities of particulate systems part 17. Settling velocities of individual spherical particles in Power-Law non-Newtonian fluids. International Journal of Mineral Processing, 143, 125–130. doi: https://doi.org/10.1016/j.minpro.2015.07.005
21. Valverde, J. M. (2013). Fluidization of Fine Powders: Cohesive versus Dynamic Aggregation. The 14th International Conference On Fluidization – From Fundamentals to Products. Available at: https://dc.engconfintl.org/cgi/viewcontent.cgi?article=1006&context=fluidization_xiv
22. Kulkarni, N. J., Mathpati, C. S., Mandal, D., Dalvi, V. H. (2019). Minimum Fluidization Velocity of Intermediate Sized Particles in Conventional and Packed Fluidized Bed. International Journal of Chemical Reactor Engineering, 17 (10). doi: https://doi.org/10.1515/ijcre-2018-0321
23. Zhong, W., Ji, X., Li, C., Fang, J., Liu, F. (2018). Determination of Permeability and Inertial Coefficients of Sintered Metal Porous Media Using an Isothermal Chamber. Applied Sciences, 8 (9), 1670. doi: https://doi.org/10.3390/app8091670