Experimental Measurements of Heat Transfer through a Lunar Regolith Simulant in a Vibro-Fluidized Reactor Oven

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Extraction of mission consumable resources such as water and oxygen from the planetary environment provides valuable reduction in launch-mass and potentially extends the mission duration. Processing of lunar regolith for resource extraction necessarily involves heating and chemical reaction of solid material with processing gases. Vibrofluidization is known to produce effective mixing and control of flow within granular media. In this study we present experimental results for vibrofluidized heat transfer in lunar regolith simulants (JSC-1 and JSC-1A) heated up to 900° C. The results show that the simulant bed height has a significant influence on the vibration induced flow field and heat transfer rates. A taller bed height leads to a two-cell circulation pattern whereas a single-cell circulation was observed for a shorter height. Lessons learned from these test results should provide insight into efficient design of future robotic missions involving In-Situ Resource Utilization.

Nomenclature

H	Simulant bed height, m
g	Earth normal gravity, N
R	Simulant bed radius, m
T_f	Furnace temperature, °C
T_i	Simulant temperature at location i along the simulant bed, °C
α	Effective thermal diffusivity, m^2/s^2
λ	Wavelength (m)

Subscript

i	Thermocouple location, varies from 1 to 6 at one inch interval

I. Introduction

As the options for affordable and sustainable exploration of the solar system by both humans and robotic systems are studied and quantified by NASA and the international space community, the utilization of local resources to displace substantial masses of mission consumables brought from Earth including oxygen, water, propellants; and materials for thermal and radiation-protection, fabrication, and construction have emerged as utterly indispensible for any but the shortest and least meaningful of missions. Despite the recognition that has been achieved for this core, enabling requirement for future exploration endeavors, programmatic support for the development of the necessary technologies to collect, extract and process lunar or planetary material resources has been very limited. Consequently, no operational capability has been developed for

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missions using local resources in environments that include partial- or near-zero gravity, extreme swings in temperature, hard vacuum, destructive contamination by abrasive and adhesive dust, etc.

Volatile constituents, especially water, are now clearly known to be present in the near-surface regolith on both the moon and Mars, and are likely present on some classes of asteroids. Other volatiles containing carbon, nitrogen and hydrogen are consistent with remote-sensing signatures obtained from the moon and limited surface measurements on Mars. These volatiles represent a feedstock for the production of propellants and life-support products including oxygen, water, hydrogen, methane, etc. that would substantially reduce the cost and risk of logistics supply from Earth. Because the volatile species can be harvested by simple heating, without chemical reactors, they may constitute the easiest resources to collect and use. It follows that developing technology to efficiently extract volatiles from lunar or Martian regolith could be the mission pathfinder for more complex resource utilization technologies to follow.

Volatile extraction from planetary regolith involves heating to drive volatile species from the regolith particles by sublimation in low-pressure environments. In dense, low thermal conductivity beds of particles, efficient heating requires convective mixing to enhance heat and mass transport. Conventional methods for processing regolith simulants have included gas fluidization, rotary kilns, tumbling mixers, and auger systems, all of which suffer fundamentally from significant power consumption and wear. Mechanical agitation or vibration has been shown to improve heat and mass transfer through enhanced particle mixing and high rates of particle renewal at heating sites. Vibration can be adequately intense to induce fluidization of a particle bed, or vibrofluidization, resulting in high rates of mixing and heat transfer, and low rates of particle attrition and elutriation.[1–3] Vibrofluidization can be implemented with single axis vibration parallel with the local gravity vector in which upward movement, induced by the reactor, is opposed by gravity.

Our earlier laboratory work[2,3] demonstrated optimal frequencies of vibration as a function of pressure for small bed-heights, i.e. on the order of the bed width, that yielded peak convective heat transfer rates. At the resonant frequency, maximum heat transfer occurred and the driving power for vibration was simultaneously reduced. The power and total energy for processing regolith in a resonant reactor could therefore be much less than for other methods that are slower and heat more system hardware mass than sample mass. Additionally, while vibrofluidization behavior nominally depends on the local gravity level, resonant vibrofluidization mixing can be adapted to a near-zero-gravity environment. Because the technology is firmly based on increasingly well-understood principles, these studies provide design guidance adaptable to larger extraterrestrial processing scales and terrestrial applications.

The work consisted of observing the vibrofluidization behavior of granular beds of an older lunar regolith simulant, JSC-1, in which the bed height, 10 cm was similar to the bed diameter, 5 cm. Extensive flow visualization studies were made over ranges of vibrational frequency and acceleration level. Heat transfer measurements were made in static beds (i.e. pure conduction through particles) and under vibrofluidized conditions. Flow characteristics within a vibrated granular bed were found to depend on both the vertical vibration frequency and the acceleration level (RMS or peak-to-peak value). For a given bed height there was an optimal frequency at which the most vigorous circulation took place, corresponding to peak heat transfer rates from an immersed heater. While increasing the acceleration at any vibrational frequency increased the heat transfer rate, the frequency at which the peak heat transfer rate occurred for any acceleration level remained approximately the same. This behavior suggested an acoustic phenomenon dominates the behavior, with the bed height and the effective speed of sound in the mixture of granular material and gas phase combining to relate the bed height to a resonant wavelength. This interpretation of the vibrofluidization behavior does not consider or require any effect on behavior of the reactor diameter.

Recent hardware concepts for a lunar regolith volatile extraction and hydrogen reduction reactor suggest the utility of a smaller reactor diameter, sized to closely approximate the diameter of a frozen core sample extracted from the lunar soil. This reactor concept, developed at the NASA Johnson Space Center, involves gas ports only at the top of the reactor and core sample and depends on diffusion to extract evolved volatiles, supply hydrogen for regolith reduction, and extract water vapor resulting from the hydrogen reduction. To provide a supplemental method for improving heat and mass transport in this reactor, the vibrofluidization reactor work at the NASA Glenn Research Center was adapted to consider the behavior of smaller diameter reactors filled to a larger bed height. Additionally, the smaller diameter reactor and the possibility of a frozen core sample required the implementation of a reactor with a heated-wall instead of an immersed heater. This paper provides some results of a laboratory capability constructed to study the vibrofluidization behavior of such a reactor scheme.

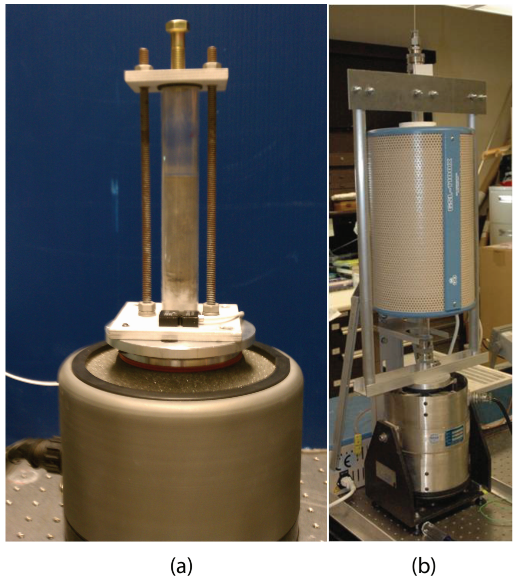

Figure 1. Pictures of the experimental setup: a) acrylic tube mounted on a shaker for flow visualization; b)quartz reactor in a tube furnace for heat transfer tests.

II. Experiments

Two types of experiments were performed during this study; cold-flow tests using acrylic tubes for flow visualization, and hot-flow tests in quartz tubes with heating. Both JSC-1 and JSC-1A lunar simulants were used in these tests. Layered colored sands were used sometimes in the acrylic tube to better visualize the flow patterns when needed.

Cold-flow Experimental Setup: Cold-flow tests were conducted using a cylindrical acrylic tube of internal diameter 18 mm and a height of 15.25 cm. The acrylic tube was filled with a lunar simulant (or colored sand) to the desired height and mounted vertically on an electromagnetic shaker table using flanges on both ends with rubber gaskets as shown in Figure 1a. The shaker table is capable of producing accelerations up to 8g's in the frequency range of 20 Hz to 80 Hz. An accelerometer mounted to the bottom flange provided acceleration measurements at 300 Hz sampling rate captured using a data acquisition system on a laptop computer. During cold-flow tests the flow patterns within the test cell were observed visually over a range of frequencies for fixed a acceleration level. Video recordings of the colored sand tests were also obtained using a CCD camera. Even though we tested at several acceleration levels in the range 3 to 8g's, we report here only the results from the 5g tests, since the results for other acceleration values were similar.

Hot-flow Experimental Setup: Hot-flow experiments were conducted using a quartz tube with in an internal diameter of 18 mm and a total height of 30 cm. The quartz tube was fitted with vacuum rated Swagelok fittings on either ends and positioned within a tube-furnace during heating tests as shown in Figure 1b. An aluminum frame that holds the quartz tube was mounted on an electromagnetic shaker so that the tube could be vibrated along the vertical axis of the furnace. A quartz wool plug was packed at the bottom of quartz-tube to position the regolith bed at the center of the furnace. A 1/8 inch stainless steel thermocouple probe with 6 type-K junctions located 2.54 cm apart starting from the tip of the probe was positioned along the centerline of the quartz tube to measure regolith temperatures and locked in place using fittings at the top. An accelerometer positioned at the bottom of the aluminum frame measured the acceleration levels. The experimental setup also had porous metal frits at the bottom for gas fluidization and a pressure transducer at the top exit, but these features were not used in this study. A schematic illustration of the hot-flow setup is shown in Figure 2.

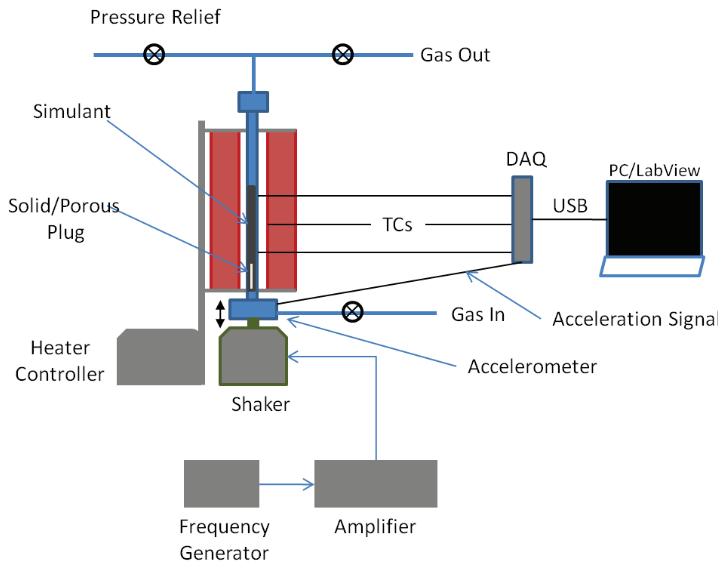

Figure 2. Schematic illustration of the heat transfer test setup.

III. Results and Discussion

A. Cold Flow Results

Prior to hot-flow tests, flow visualization tests were performed in an acrylic tube using both JSC-1 and JSC-1A with a bed height of 12.5 cm. This bed height was dictated by the by the current design of the RESOLVE reactor at NASA/JSC with its many system level constraints. The tube diameter of 18 mm corresponds to the core diameter of the drilling mechanism. Our initial cold-flow tests using JSC-1A revealed that the mixing and circulation was not as vigorous as our earlier tests with JSC-1 simulant at a lower bed height ($\sim$6 cm) even when the excitation frequency was varied over the same range of 20 to 80 Hz at a peak-to-peak acceleration of 5g. While some particle circulation was observed at the top and bottom of the tube, a section of the regolith-bed close to the center remained relatively stationary with very little observable particle movement. We also observed size segregation in JSC-1A, where larger particles migrated to the top and bottom of the tube while fine particles stayed close to the center where they coalesced almost into a rigid pack. Repeating the tests with JSC-1 simulant at the same bed height showed a similar flow pattern, with a relatively dead region in the middle and mixing close to the top and bottom of the tube. However, the resulting flow velocities are more vigorous in JSC-1 compared to JSC-1A which has a smaller particle size distribution (mean particle size $\sim$ 190 μm). This observation appears consistent with the Geldart's classification of fluidizability of powders.[5,6] JSC-1A with its finer particle size is more cohesive and the inter-particle forces (such as van der Waals forces) are stronger than the drag forces induced by gas motion. JSC-1, on the other hand, with its larger particle sizes is influenced more by the gas motion leading to better flow circulation. The best overall circulation for both simulants was observed close to an excitation frequency of 40 Hz, though with the two-cell circulation pattern and a relatively dead zone in the middle. It is worth noting here that it is hard to visualize clearly circulation patterns of the lunar simulants because of the finer particles sticking to the interior wall of acrylic tube due to electrostatic charging.

To further confirm this new two-cell circulation pattern with a relatively dead zone in the middle tests with colored sand were conducted. Different colored sands were poured into the acrylic tube in layers (see, frame 1 of Figure 3) up to a total height of 12.5 cm. The tube was than subjected to vertical vibration at 40 Hz and 5g acceleration. The resulting motion was video recorded for further analysis. Figure 3 shows a series of still images obtained from the video, starting at time zero at approximately 5 second intervals. It is clear from these pictures that the circulation pattern within the tube is divided into two cells. The size of the dead zone that is seen in the middle is relatively large at the beginning of the test, but quickly narrows as the two-cell circulation pattern develops with time. We anticipate that the circulation patterns in JSC-1 and JSC-1A simulants are similar to the colored sand test even though the particle size distributions are different. The dotted lines in the last frame show the flow path-lines in the two cell structure.

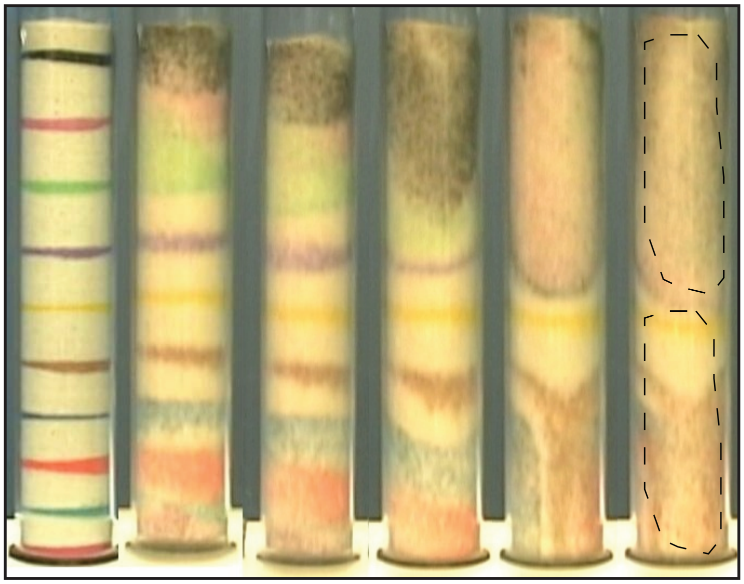

Figure 3. Still image showing the two-cell mixing mode starting from time t=0 at 5 second intervals.

Our earlier study showed that the most vigorous mixing occurs when a standing sound wave is established within the regolith bed. In those experiments the bed height was approximately 6 cm and only the first resonant mode ($H = \lambda/4$) was observed with the optimal frequency close to 60 Hz. On the other hand, in the present experiments the bed height has been increased to 12.5 cm and we suspect that the next higher hormonic wave ($H = 3\lambda/4$) prevails within the granular bed leading to two cell configuration.[4] Clearly further studies are needed, including pressure measurements within the granular bed, to fully understand this phenomenon.

B. Heat Transfer Results

Heating tests were conducted using both JSC-1 and JSC-1A simulants, again with a bed height of 12.5 cm, with and without vibration. For the vibration tests the frequency and peak-to-peak acceleration were held constant at 40 Hz and 5g's, respectively. During these tests the quartz tube was filled first with the desired simulant with the thermocouple probe inserted in the middle such that the first TC junction (TC-1) was at the bottom of the regolith bed. The last thermocouple junction (TC-6) was just above the simulant bed. The mass of the simulant for each test was approximately 47.5 grams. The tube-furnace was programmed to heat up from room temperature to 900° C in 30 minutes. In some tests, the oven was programmed to maintain 900° C for a short period of time and then allowed to cool with the power turned off. The temperature feed-back control system of the furnace heated up the furnace at a fairly uniform rate. The furnace temperature (T_f) was measured at the mid-height of the furnace in the air-gap between the quartz tube and the furnace wall and it is used to control the heating rate. Figure 4a shows the furnace temperature as a function of time for all four test results presented in this section. From Figure 4a it is safe to assume that the heating profile is essentially the same for all the tests, though the furnace control algorithm cycles the power on-and-off at different times to maintain the imposed heating profile. The measured temperatures along the simulant bed at various locations are shown in Figure 4b as function of time for the conduction (i.e., no vibration) test using JSC-1A. The top thermocouple (TC6) was slightly above the simulant bed and shows a slightly higher temperature.

Figure 5 shows a plot of temperature differences between the furnace (T_f) and temperatures at different locations (T_i) along the centerline (approximately) of the regolith bed. Vibrofluidization was not active during these tests and conduction through the simulant bed dominates the heat transfer process. DT-1 corresponds to the temperature difference at the bottom of the bed while DT-6 to the top. As mentioned

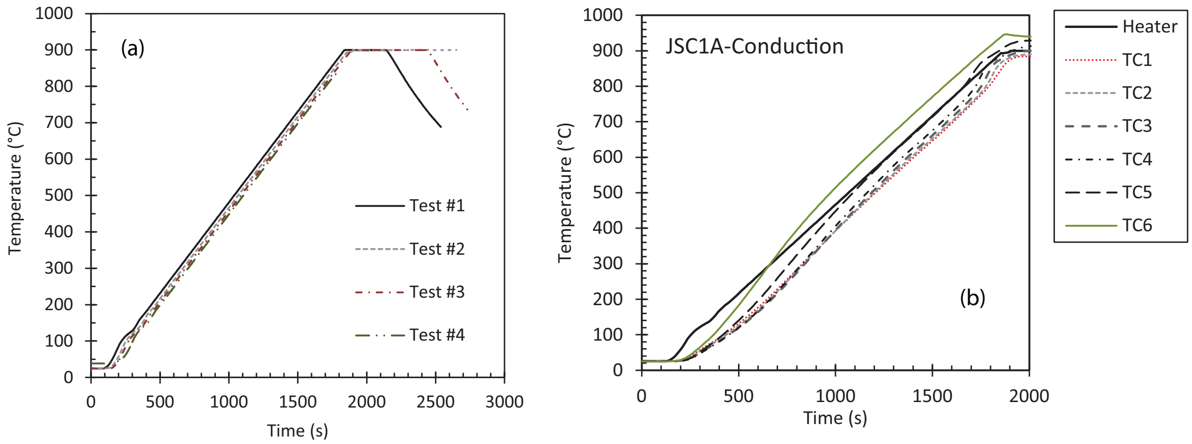

Figure 4. Furnace temperature as a function of time (a), and JSC-1A simulant temperature at various axial locations during conduction test (b).

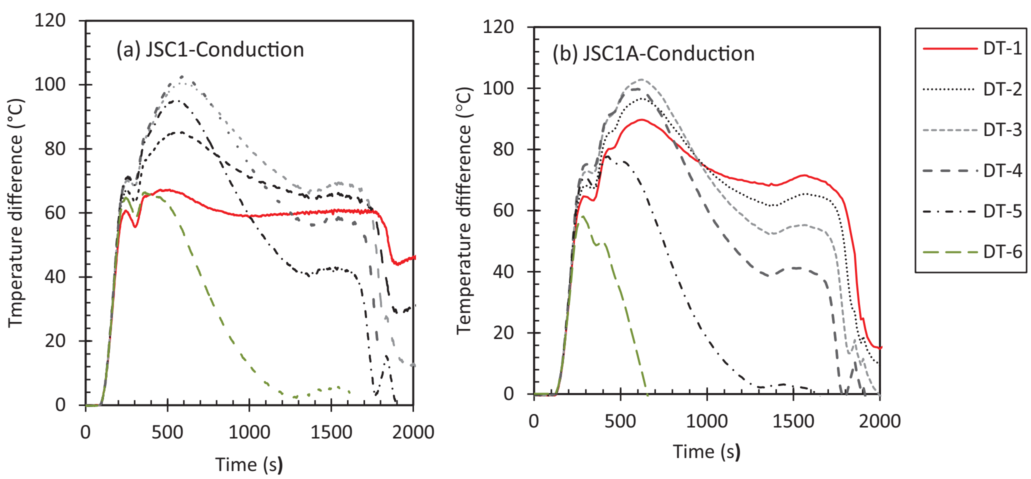

Figure 5. Temperature difference at various locations during conduction tests.

previously, the thermocouples were located 1 inch apart. It should be noted that the furnace temperature along its axis is not uniform due to its vertical orientation with respect to gravity. In the small gap between the furnace wall and the quartz tubes's outer surface, natural convection takes place and causes a positive temperature gradient with furnace wall temperature increasing from bottom to top. It is hard to discern a clear trend in temperature differences along the bed height from Figure 5, since the precise locations of the top and bottom thermocouples depend on how the simulant material was poured into the quartz reactor with the thermocouple probe in place. However, it is clear from the figure that the temperature differences between the furnace and the simulant are generally in the range of 0 to 100°C.

Figure 6 shows the temperature differences measured for the two simulants with vibrofluidization. The figure clearly shows that the simulant bed is better mixed under vibration and maximum temperature differences are in the range of 0 to 60°C. It is also interesting to note that JSC-1 simulant (Fig. 6a) shows a better temperature uniformity compared to JSC-1A (Fig. 6b) within the reactor since all the DT_i curves are closer together, except for DT-6 which may have been in the gas-phase. This observation agrees with the flow visualization test which showed better mixing in JSC-1 compared to JSC-1A. The temperature differences in JSC-1A with vibration are still smaller compared to the conduction tests but slightly higher than the JSC-1 case as expected.

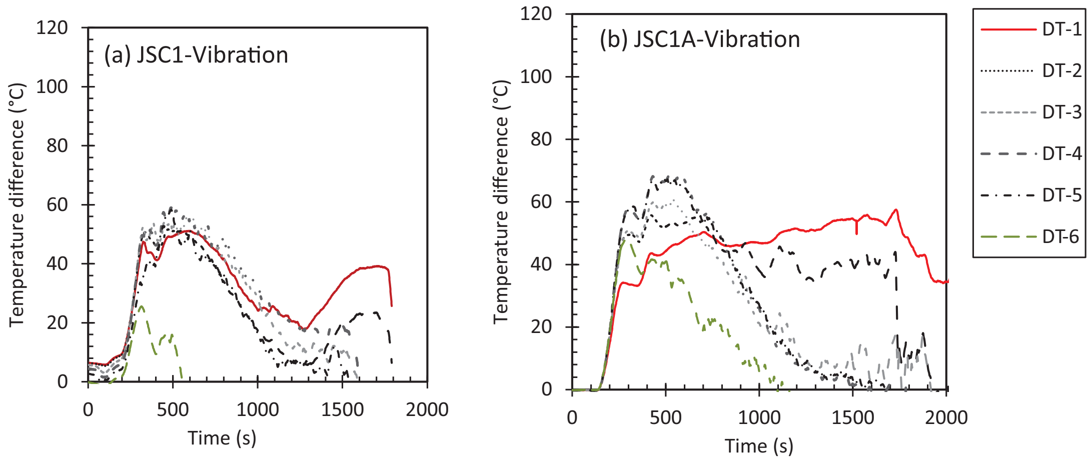

Figure 6. Temperature difference at various locations during vibration tests.

A common feature exhibited in Figures 5 and 6 is the initial rapid rise in temperature difference reaching a peak and then a slow decline or leveling off. The peak occurs at around 700 seconds for the conduction tests while vibration tests take around 600 seconds. One possible explanation is that this initial behavior corresponds to the starting transient which is of the order of R^2/α, where R is the radius of the reactor tube and α is the effective thermal conductivity of the simulant material. With $R = 9 \times 10^{-3}$m and a value for α about 10^{-7} m^2, we estimate this time to be around 600 seconds which is of the same order of the experimentally observed values. However, more importantly the peak temperature differences are lower and the DT-traces are closer for the vibrated case compared to the conduction case. The implies that the heating of the material under vibration is more rapid and uniform.

IV. Concluding Remarks

Preliminary tests were conducted using JSC-1 and JSC-1A lunar simulants, with and without vibrofluidization, in order to examine the mixing flow patterns and heat transfer characteristics. The results show that it is harder to vibrofluidize granular material with finer particles compared to larger particles, as in the case of JSC-1 and JSC-1A, respectively. These observation are in accordance with the Gerdalt's classification of gas-fluidizability of granular material. It has also been shown that taller granular bed heights ($\sim$ 12.5 cm) leads to two-cell circulation pattern with a relatively quiescent zone in the middle, where as shorter bed heights ($\sim$ 6 cm) exhibit single cell, vigorous mixing pattern for the same range of excitation frequencies and acceleration. These observations may have important implication with respect to the "beneficiation" processes used prior to processing a drilled core material, and in the design of furnaces using vibrofluidization as a mixing mechanism.

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