

# **An Investigation into the Effects of Vibration and Aeration on Powder Flow through Hoppers**

## **Research Proposal**

**Submitted to**

**International Fine Particle Research Institute  
(IFPRI)**

**By**

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## 1. Problem

Hoppers and silos are extensively used for transfer and storing of bulk solids in various industries, such as powder, cement, chemical, pharmaceutical, food, paint etc. In spite of having well established Jenike method (ASTM D6128) for designing of hoppers, power flowability problems (such as arching, funnel flow, rat-holing etc.) frequently exist in industry for the possible reasons of:

- Variation in powder properties at site - the actual powder could be finer and/or lighter compared to the powder tested for flowability at design stage i.e. differences in physical properties.
- The powder might have gained moisture and could have become cohesive – could be due to rainy season and/or heater in fluidizing line is not effective.
- Segregation of powders – the finer powders could be more unevenly distributed towards the hopper wall causing an increase in wall friction.
- Buildup of powders and/or the rusting/unevenness on the inner wall of hopper/silo – could cause an increase in wall friction.
- Venting could be too strong - causing a high negative pressure against the gravity flow.
- The hopper/silo wasn't well designed in the first place.

In order to counter such problems or potential problems, hoppers/silos are often provided with flow assistance arrangement, such as vibration and aeration systems. However, the design/selection of such flow-promoting devices lack clear guidelines in terms of:

- Relation between the powder properties (such as median size, size distribution, shape, bulk densities and moisture content) and hopper condition (plane versus cylindrical hopper, hopper slope, outlet dimension and state of stress) with the amplitude, frequency, orientation of vibration and optimal placement of the same.
- Relation between the powder properties (such as median size, size distribution, shape, bulk densities and moisture content) with the type of aeration device, air flow, air pressure and optimal placement of the same.

## 2. Summary of literature review

Annexure-I provides detail literature review from Kollman and Thomas (2002) to Hartig et al. (2022) on vibration and aeration arrangement applied in hoppers. The following are some of the key results:

- Vibration facilitates flow by reducing shear resistance and wall friction. With an increase in vibration velocity, there is a notable decrease in the shear force necessary to initiate flow, with the wall friction angle exhibiting the greatest sensitivity. High-frequency, low-amplitude vibrations (60–80 Hz) effectively disrupt cohesive arches by breaking inter-particle bonds, whereas low-frequency, high-amplitude vibrations (~15 Hz) cause bulk particle displacement without significantly affecting particle cohesion.
- The vibrator's positioning is crucial; situating it near the hopper outlet (approximately 50 mm) significantly enhances discharge continuity. Conversely, placements at greater distances (e.g., 150 mm) lead to frequent interruptions in flow. Under jammed conditions, localized vibrations near the outlet are effective in disrupting arching and reinstating flow.

- Pulsated aeration enhances vibration by fluidizing and disrupting agglomerates via rhythmic airflow. Square-wave pulsation (1–50 Hz) reduces the minimum required airflow by more than 50% in materials such as pulverized coal, enhances discharge rates by approximately 20%, and stabilizes flow. Frequencies exceeding 1 Hz result in continuous discharge, while lower frequencies are associated with intermittent flow. Pulsation functions by reducing channel formation and enhancing uniform aeration.
- A novel alternative to external vibration or gas injection is the implementation of a flexible wall system (e.g., rubber air spring), wherein internal cavity pressure fluctuations (up to approximately 125 Pa) result in membrane expansion and contraction. This mechanism simulates aeration by creating air voids that traverse the powder bed, thereby collapsing arches and facilitating discharge. Optimal performance occurs when air is injected near the arch formation zone, approximately 40 mm above outlet, which aligns pressure disturbances with structural weaknesses in the powder bed.
- Coupled CFD-DEM simulations and continuum models yield valuable predictive insights. CFD-DEM effectively models particle dynamics, illustrating hopping motion in fine cohesive powders and inter-layer shearing in coarser particles. The model combines how particles interact with each other and with surfaces using Hamaker constants and tracks the effects of cohesion with granular Bond numbers, showing that flow is limited when cohesion is high and throw intensity is low. Continuum models such as the Stress Arc theory enhance the Discrete Element Method (DEM) by predicting bulk flow behavior and stress distribution in hoppers. Both modeling methods show a strong agreement with experimental results, helping to create better systems that use vibration, air flow, and structural changes to effectively manage cohesive powders.

### 3. Gaps in current research

A review of the literature shows the following limitations:

- Significantly less amount of research has been carried out till date in the area of flow assistance to hoppers (through vibration and aeration), compared to some of the other areas of bulk solids handling such as pneumatic conveyor, flow properties, segregation etc.; and as a result, the available results and inferences are potentially limited to only certain bulk solids, wall surfaces and loading conditions.
- Even within the narrow range of bulk solids that have been tested, most of the materials are coarse (and not fine powders); fine powders are the ones which typically show hopper discharge problems (due to arching and rat-holing) and very fine powders are difficult to be fluidized due to channeling.
- There is no comprehensive relation/model/results between the powder properties (such as median size, size distribution, shape, bulk densities and moisture content) and hopper condition (plane versus cylindrical hopper, hopper slope, outlet dimension and state of stress) with the amplitude, frequency, orientation of vibration and optimal placement of the same, also there is no comprehensive relation/model/results between the powder properties (such as median size, size distribution, shape, bulk densities and moisture content) with the type of aeration device, air flow, air pressure and optimal placement of the same.

#### 4. Project objectives

In view of these limitations of the existing state of research, a comprehensive experimental and simulation (Discrete Element Method – DEM) study is required with the following objectives:

- To develop new and to augment existing test facility comprising of developing shear cell with vibration and aeration arrangements of different types (different amplitude, frequency of vibration, different types of aeration such as stainless steel and ceramic pads, direct air injection through inverted nozzle etc.), i.e. to develop modified Jenike shear cell tester, developing transparent hoppers of conical and plane type with vibration and aeration arrangements of different types, angle of repose tester with vibrating base for DEM calibration, fluidization-deaeration tester with inclined base.
- To carry out shear testing (flow function and wall friction) under instantaneous and time consolidation state using standard Jenike tester and modified Jenike tester and to carryout hopper flow tests using transparent plane and cylindrical hoppers having different hopper half angles and outlet dimensions under without and with vibration and aeration condition for different amplitude, frequency of vibration, different types of aeration devices such as stainless steel and ceramic pads, direct air injection through inverted nozzle etc., angle of repose testing with and without vibration to the base, fluidization-deaeration testing with horizontal and inclined base for a wide range of bulk solids having different particle size distribution, loose poured bulk density, shape etc.
- To carryout DEM simulation for hopper flow with and without vibration, including calibration and modelling for powders/particles having different size distributions, shapes and solids densities for understanding the fundamental mechanism of powder flow based on particle-particle-wall interactions under different vibration parameters.
- To carryout CFD-DEM simulation for hopper flow with and without aeration, including different types of aeration systems (stainless steel versus ceramic pads, inverted nozzles etc.) for powders/particles having different size distributions, shapes and solids densities for understanding the fundamental mechanism of powder flow based on particle-air-wall interactions under different aeration parameters.
- To formulate an appropriate model(s) (analytical/empirical/semi-empirical) that characterizes force and velocity distributions across different hopper geometries under vibrational excitation, and to investigate the effects of key vibration parameters, such as amplitude, frequency, and acceleration, on internal stress fields and the mechanisms driving powder flow, hopper unjamming and flow enhancement and to validate the model against hopper test data.
- To formulate appropriate model(s) (analytical/empirical/semi-empirical) that characterizes fluidization for different hopper geometries under different pads and aeration conditions, and to investigate the effects of key aeration parameters, such as air flow, pressure, nature of air distribution, location optimization etc. on the mechanism of powder flow under aerated condition and to validate the model against hopper test data.
- To design and develop optimized vibration and aeration system (based on laboratory scale testing, simulation and results of analytical modelling) for plant scale implementation and to carry out site-testing by installing the developed system in industrial hoppers/silos with performance measurement and by taking cognizance of any operational and maintenance issues.
- To develop a Design Guide backed by the improved understanding from experimental work and using validated DEM/DEM-CFD simulations and analytical modelling, site testing/site-validation, wide

range of results would be developed for optimum selection and application of vibration system, such as vibration system – frequency, amplitude, location, direction and aeration system – air flow, pressure, distribution/surface area, location etc. for a wide range of bulk powder characteristics (different size distribution, shapes, moisture content and bulk densities) and hopper conditions (hopper half angle, outlet dimension and consolidation load).

## 5. Experimental work

The following tests will be carried out for a wide range of powders having different particle size distribution, shape and loose poured bulk densities:

Sl No.	Test	Test facility required	Whether test facility is available at institute or to be fabricated/ purchased or outsourced
1	Loose poured bulk density	Hall flow meter/ Scott volume meter	Available at the institute
2	Particle size distribution	Malvern Master Sizer or similar equipment operating under laser diffraction method	To be outsourced
3	Particle shape	Scanning Electron Microscopy (SEM)	Available at the institute
		Malvern morphology or similar equipment	To be outsourced
4	Powder flow function and wall friction testing without vibration and aeration	Jenike shear tester	Available at the institute
5	Powder flow function and wall friction testing with vibration	Shear cell of the existing Jenike tester and wall material/coupon will be modified to include vibration input – to be fabricated, the vibration arrangement including vibration module, frequency and amplitude control system and other accessories	To be fabricated/ purchased
6	Powder flow function and wall friction testing with aeration	The shear cell of the existing Jenike tester and wall material/coupon will be modified to include aeration of different types – to be fabricated, the aeration arrangement including blower/compressor, air flow meter, membrane, flow and pressure control valves, air heater, pressure and temperature gauges	To be fabricated/purchased

7	Fluidization-deaeration and minimum fluidization velocity	Fluidization-deaeration tester with fluidizing air circuit consisting of flow control valve, air heater, pressure and temperature gauges, blower/fan	Available at the institute
8	Fluidization-deaeration and minimum fluidization velocity against inclined surface	The base part of the existing fluidization/deaeration tester will be modified with different inclination angle and the vertical transparent tube is to be cut accordingly in oblique plane	To be fabricated/ purchased
9	Angle of repose without vibration	Angle of repose tester	Available at the institute
10	Angle of repose with vibration	The base part of the existing angle of repose tester will be amended to provide vibration input	To be fabricated/ purchased
11	Power response to vibration and aeration	Transparent plane and conical hopper in different combinations of outlet opening and hopper half angles	To be fabricated/ purchased

The base of the existing Jenike shear tester and wall material/coupon will be amended to include vibration input and aeration (see Figure 1 and 2). The purpose of these will be to test flow function and wall friction under vibration and aeration conditions. The amended shear tester with vibration input will be inspired by arrangement mentioned in Kollman and Thomas (2002). Various vibrators (e.g., electromagnetic, pneumatic, and rotary) will be tested, with control over amplitude, frequency and acceleration. The vibration circuit is shown in Figure 3. Vibration will be applied with different parameters during flow function and wall friction testing. The results of flow function and wall friction testing with and without vibration will be compared and could be used as experimentally derived parameters in subsequent modelling (empirical/semi-empirical). In summary, tests will be carried out by varying the following powder, vibration and test conditions:

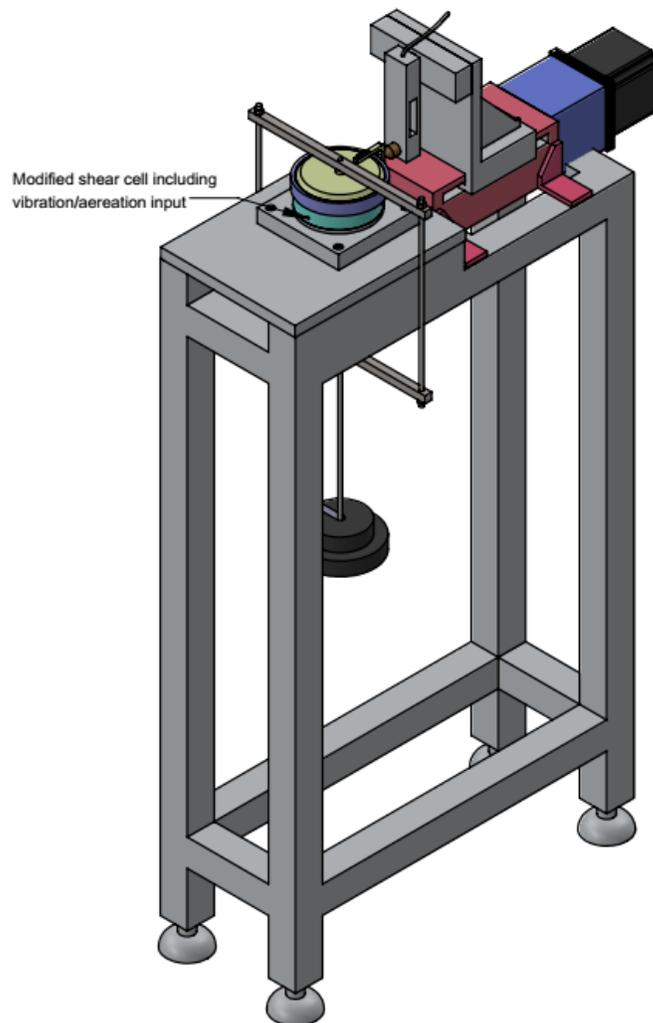
- Type of vibrator - electromagnetic, pneumatic, and rotary
- Amplitude, frequency, acceleration
- Powder size distribution, shape, loose poured bulk density
- Type of wall material – stainless steel (SS 304/316), mild steel etc.
- Different instantaneous and time consolidation loads

Refer to Figure 1 and Figure 4, the amended shear tester with aeration input is shown. It comprises of a compressor/blower, flow control valve, flow meter, pressure gauge, temperature gauge etc. In case a well distributed aeration is to be provided, the air will be passed through several tiny apertures either directly or through strips of fluidizing membranes. The aeration circuit is shown in Figure 4. Aeration will be applied with different parameters during flow function and wall friction testing. The results of flow function and wall friction testing with and without aeration will be compared and could be used as experimentally derived parameters in subsequent modelling (empirical/semi-empirical). In summary, tests will be carried out by varying the following powder, aeration and test conditions:

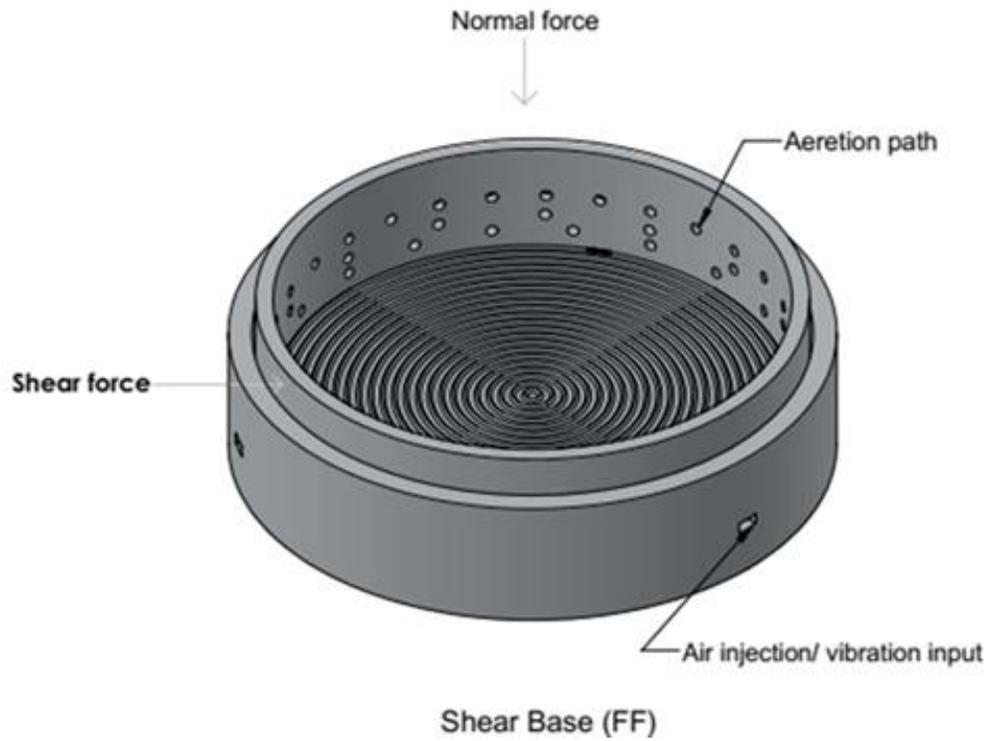
- Type of aeration – fluidizing pad/perforations spread across a surface versus pointed nozzle inlet

- Air flow and pressure
- Powder size distribution, shape, loose poured bulk density
- Different instantaneous and time consolidation loads

Figure 5 shows existing and a modified fluidization-deaeration chamber with inclined base. The angle of inclination of the based can be varied and accordingly transparent cylindrical section will have different matching oblique planes. Quality of fluidization will be observed and minimum fluidization velocity will be determined for different slope angles and will be compared against those obtained from the usual fluidization-deaeration test chamber having a horizontal base.



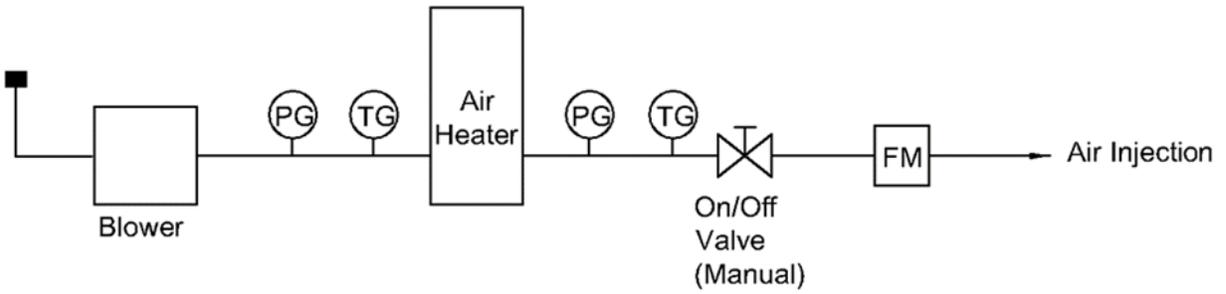
**Figure 1:** Existing Jenike shear cell set-up with amended basis – total view



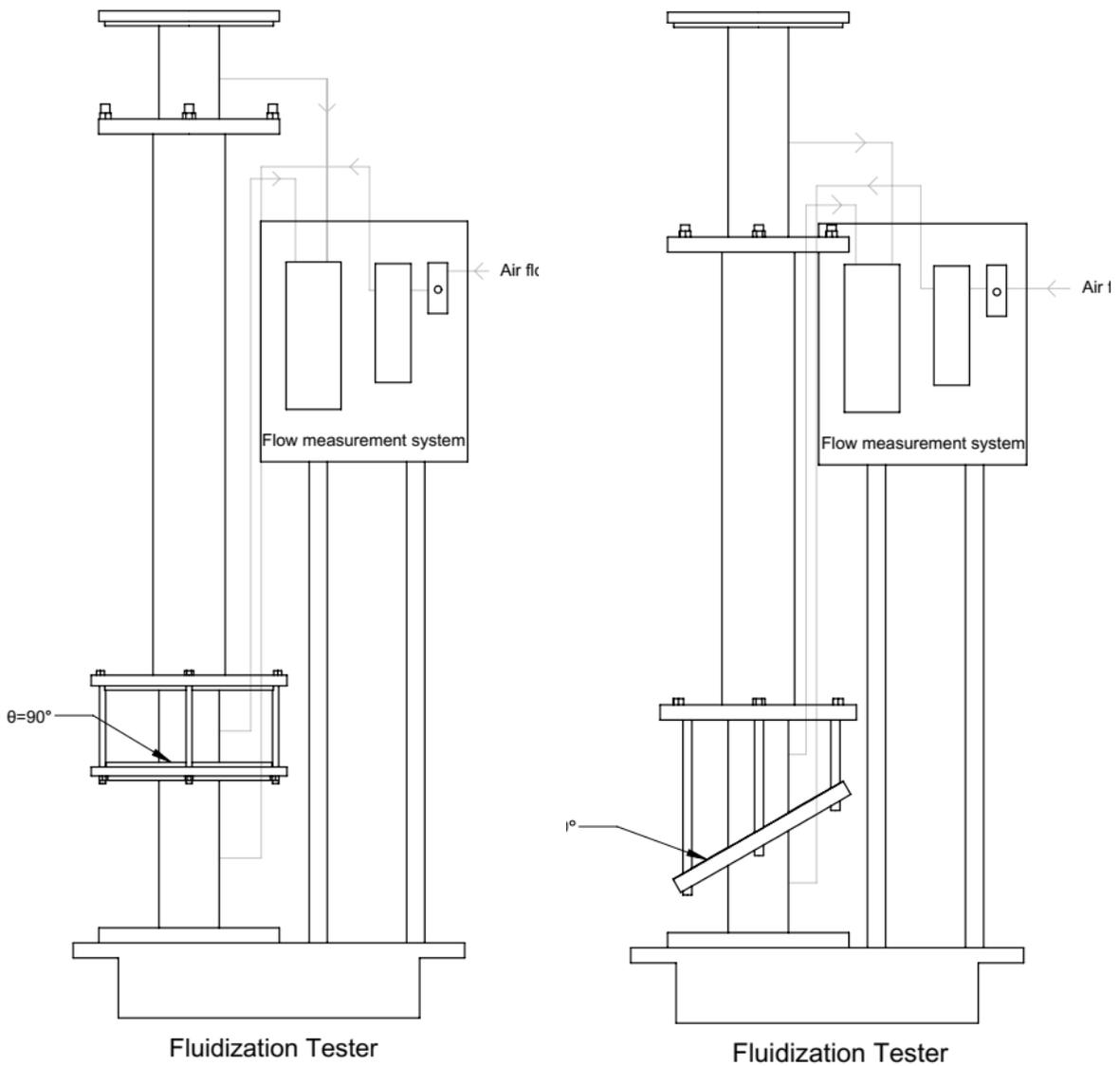
**Figure 2:** Modified base of Jenike shear cell incorporating vibration and aeration inputs



**Figure 3:** Vibration circuit in modified Jenike shear cell base



**Figure 4:** Air injection circuit for modified Jenike shear cell base



**Figure 5:** Existing (left) and amended (right) fluidization-deaeration test set-up

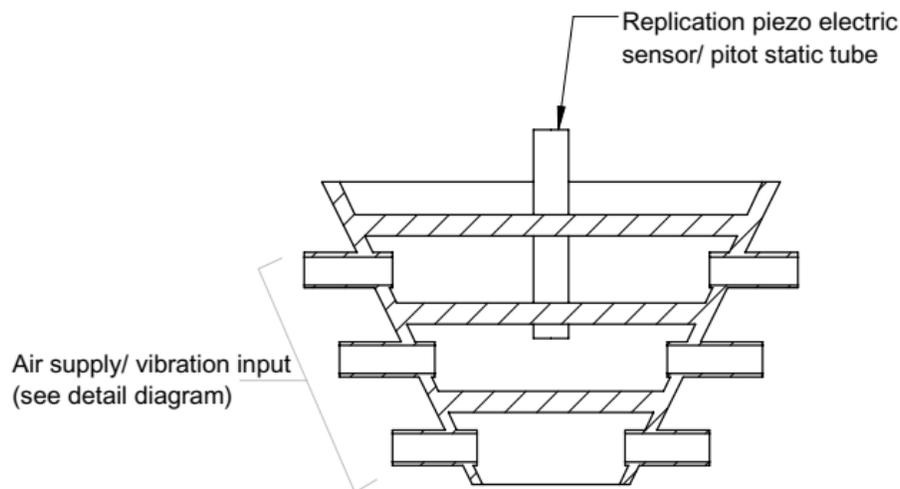
Refer to Figures 6 and 7. A group of transparent hoppers will be developed for improved understanding of the mechanism of vibration and aeration (i.e. the response to powders to vibration and aeration). These hoppers will have different hopper half angles and outlet dimensions. Hoppers will be both plain type and cylindrical. These hoppers will be installed with arrangement for vibration and aeration input. Various vibrators (e.g., electromagnetic, pneumatic, and rotary) will be tested, with control over amplitude, frequency and acceleration. Force sensors and accelerometers will be placed at critical locations (walls, base, and inside the powder body) to record vibration transmission and wall stress responses. In case of aeration, sensitive air velocity/flow meter will be placed inside the powder body at different locations to measure airflow. These measured data (of vibration and aeration) will be used to validate the analytical model. In the hoppers powders will be placed layer by layer (powders having different colors) in both horizontal and vertical directions to observe the layer movement/powder mixing/powder flow for better understanding on the effect of the flow mechanism when powders are subjected to vibration and aeration as compared to not subjected to vibration and aeration.

The vibration circuit would typically include:

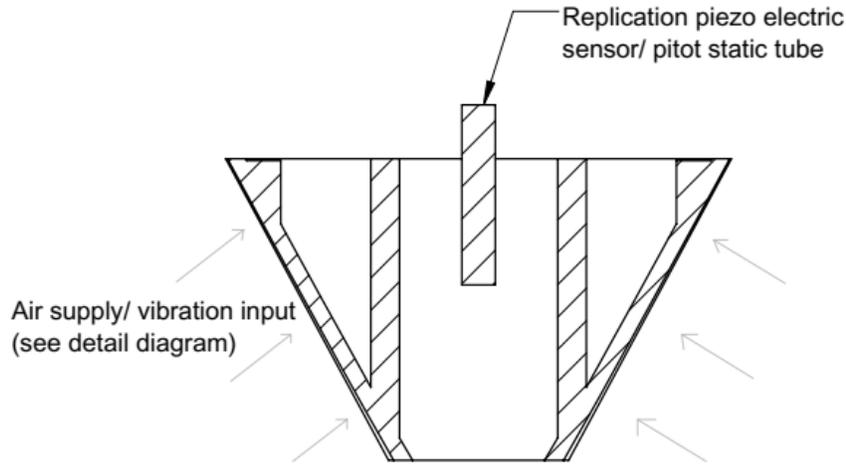
- Vibrators: Electromagnetic Vibrators (10 N, 100N, 500N, in pairs), Function Generator, Amplifier, Power Supply and Vibration Controllers
- Measurement and Sensing Equipment: Accelerometers, Load Cells/ Force Sensors, Displacement sensors/ LVDTs, Sensors/PZT accelerometers for the measurement of vibration field of powder flow
- Data Acquisition and Processing: DAQ system, Oscilloscope/Data Logger, Software for Signal Processing (MATLAB, LabVIEW, COMSOL etc.), Workstation

The fluidizing circuit (already available at the institute) would typically include:

- Blower: 50 Nm<sup>3</sup>/hr with capacity with flow control valve or air compressor: 50 Nm<sup>3</sup>/hr, 7 bar discharge pressure with flow control valve and pressure reducing valve.
- Electric heater: 20-120°C, pressure and temperature gauge, air flow meter



**Figure 6:** Transparent hopper with horizontal powder layers



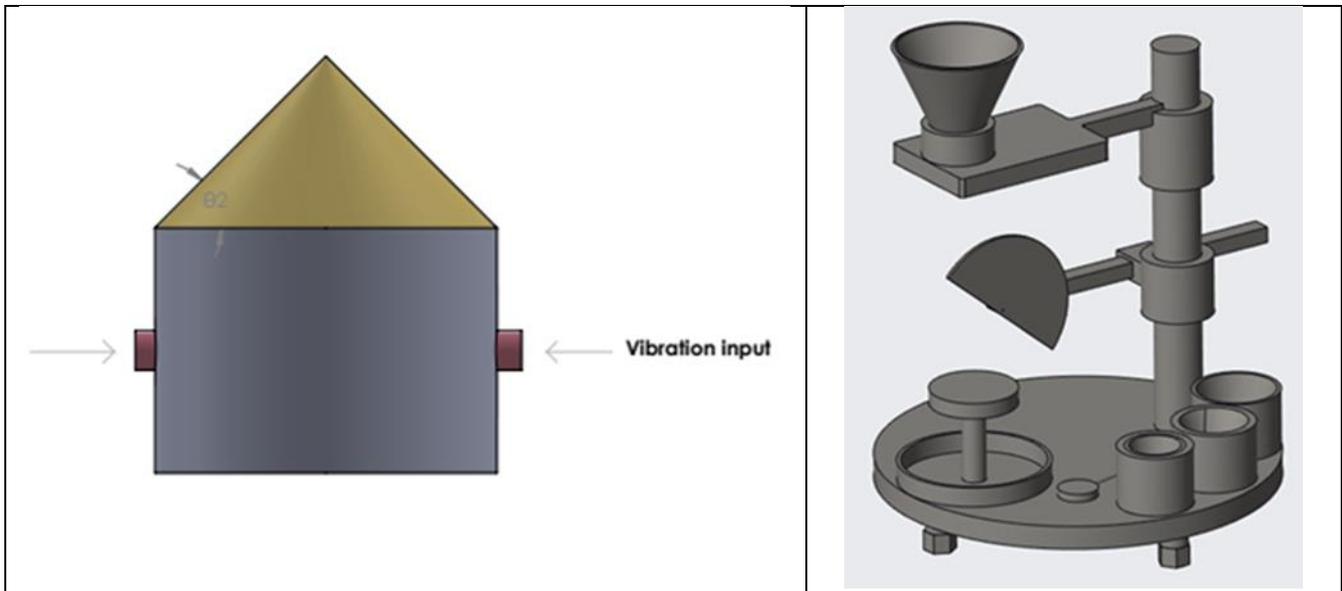
**Figure 7:** Transparent hopper with vertical powder layers

## 6. Discrete Element Simulation (DEM)

DEM and DEM-CFD coupled modelling will be carried out for simulation and understanding of the mechanism of powder flow under the application of vibration and aeration, respectively, using the following facilities:

Sl No.	Simulation	Facility required	Whether simulation facility is available at institute or to be purchased
1	DEM/ DEM-CFD	ALTAIR DEM/DEM-CFD license	Available at the institute
2	Workstation	DELL Precision 5820 Tower	Available at the institute

In addition to the standard/basic calibration tests for DEM (such as bulk density and angle of repose tests), angle of repose testing will be carried out with a vibrating base connected to the vibration circuit (similar to the vibration circuit shown previously), as given in in Figure 8, for the purpose of calibrating the DEM model. DEM simulation will be carried out by constructing hoppers of same dimensions as the transparent hoppers (see Figure 6 as typical) and by applying vibration (with different amplitude, frequency etc.) at different positions of the hopper wall in the simulation environment. Similarly DEM-CFD simulation will be carried out by constructing hoppers of same dimensions as the transparent hoppers (see Figure 6 as typical) and by applying aeration (with different air entry configurations, air flow, air pressure etc.) at different positions of the hopper wall. Sensors will be placed in DEM and air velocity, vibration amplitude etc. will be measured in simulation and will be validated against the experimental findings. Simulation will be carried out with particles of different size distribution, shape, bulk density etc.



**Figure 8:** Modified angle of repose tester with vibration added to the base for DEM calibration

## 7. Analytical modelling

The analytical modelling aims to quantify how vibrational excitation alters the mechanical behavior of cohesive granular material within a conical hopper. This begins with static equilibrium formulations to define baseline stress and velocity fields and is subsequently extended to incorporate the dynamic effects of vibration, such as oscillatory body forces and stress redistribution. The objective is to predict the effect of vibration parameters on flow initiation, stress transmission, and unjamming thresholds in granular systems and would comprise of the following:

- **Stress Distribution in Static Conditions:** Under gravity alone (no vibration), the vertical stress in conical and wedge hopper (governed by Mohr-Coulomb-based approximations).
- **Stress Distribution under Vibrational Influence:** The stress field inside the granular medium will be modelled analytically to incorporate the effects of oscillatory inertial forces generated by vertical or radial vibrations. Incorporating time-dependent body acceleration into the stress equations will facilitate the assessment of how transient stresses influence particle rearrangement and unjamming mechanisms during flow.
- **Velocity Field Estimation:** Velocity distributions within the hopper will be assessed utilizing existing or new model(s). These formulations will be expanded to incorporate the effects of vibration factors, facilitating the prediction of improved particle mobility and flow rate under various vibratory conditions.
- **Wall Forces and Stress Redistribution:** We will examine the impact of vibrations on particle-wall interactions, emphasizing the reduction of normal contact forces and the modification of wall shear stress. The model will incorporate dynamic estimations of wall friction based on vibration amplitude, frequency and acceleration. The radial and axial stress components will be reassessed to enhance comprehension of their influence on force chain disruption and the alleviation of jamming at the hopper exit.

Similarly, modelling for aeration would comprise of the following:

- **Continuum Modeling of Bulk Particle Behaviour:** The hopper contents will be modelled as a continuum material following frictional-cohesive constitutive laws, such as the Mohr-Coulomb, to capture cohesive arch formation and flow blockages. This would result in prediction of stagnant zones, arch stability conditions, and identification of critical regions prone to obstruction.
- **Coupled Fluid-Particle Interaction Modeling:** Air-particle interaction will be modelled by coupling particle flow equations with Darcy's law or a two-phase flow framework, where fluidizing air would influence inter-particle forces and diminishes particle-particle cohesion. This coupling would result in prediction of fluidization air induced stress distribution and increased particle mobilization.
- **Prediction of Flow Regimes and Discharge Behaviour:** Analytical or semi-analytical relationships will be developed by linking air injection parameters to discharge rates, flow regime, and hopper emptying phenomenon enabling generation of flow curves and operational maps and optimization for type and placement of air injection.

The nature of model could be purely analytical, but more likely the models may include some parameters from experimental work that would capture the bulk powder behavior. The analytical models will be validated against experimental results of transparent hopper flow (ref Figures 6 as typical).

## **8. Plant scale development and site testing**

Based on the results obtained from experimental, simulation and analytical work, optimized vibration and aeration system will be designed and developed for plant scale implementation/site-testing. Appropriate number of industries/plants will be identified that are handling wide range of cohesive/difficult to flow powders and the optimized vibration or aeration system will be installed in such hoppers/silos. Site testing will provide product flow rate (mass or volume based depending on site condition), capability to overcome flow jamming in practical scale with and without the new developed system. The system will be integrated to the operational logic of the existing system and will be tested at site for 3 to 6 months to observe any operational and maintenance issues.

## **9. Design guideline**

As the outcome of this project, a comprehensive **Design Guideline** will be developed. This guideline will be based on the enhanced understanding obtained through detailed experimental investigations, validated Discrete Element Method (DEM) and coupled DEM-Computational Fluid Dynamics (DEM-CFD) simulations, as well as analytical modeling. An extensive set of results will be generated to enable the optimum selection and application of flow-assisting systems. The Design Guideline will cover key parameters for **vibration systems** — including vibration frequency, amplitude, location of application, and direction of vibration — as well as for **aeration systems**, including factors such as air flow rate, air pressure, distribution/surface area, and placement/location of aeration units. The guideline will be developed to address a wide range of **bulk powder characteristics**, taking into account variations in particle size distribution, particle shapes,

moisture content, and bulk densities. It will also consider the influence of different **hopper conditions**, such as hopper half-angle, outlet dimensions, and consolidation loads. The Design Guideline will serve as a practical tool for industry practitioners, enabling them to systematically select and design flow assistance systems that are optimal for their specific applications.

## 10. Project schedule

Particulars	Months					
	6	12	18	24	30	36
Hiring of project staffs	√					
Upgradation of shear cell tester for vibration input	√					
Upgradation of shear cell tester for aeration input	√					
Development of vibration input circuit		√				
Development of aeration input circuit		√				
Development of test facility for DEM calibration	√					
Powder purchase and physical characterization		√				
Powder testing in modified shear cell for vibration		√	√	√		
Powder testing in modified shear cell for aeration		√	√	√		
DEM calibration and modelling, DEM simulation for vibration		√	√	√		
DEM calibration and modelling, DEM/CFD simulation for aeration		√	√	√		
Development of transparent hoppers for testing			√	√		
Vibration circuit development for transparent hoppers			√	√		
Aeration circuit development for transparent hoppers			√	√		
Analytical modelling for vibration input in hoppers				√	√	
Analytical modelling for aeration input in hoppers				√	√	
Vibration test in transparent hoppers				√	√	
Aeration test in transparent hoppers				√	√	
Development of optimized vibration system for site testing					√	
Development of optimized aeration system for site testing					√	
Installation of optimized vibration module in industry and testing					√	√
Installation of optimized aeration module in industry and testing					√	√
Development of Design Guide						√
Apply for patents and/or publications						√

## 11. Budget

Sl No	Item	Year 1 USD	Year 2 USD	Year 3 USD	Total USD
1.	Fabrication (laboratory scale development) <ul style="list-style-type: none"> <li>• Vibrators: Electromagnetic Vibrators (10-500N, in pairs), Function Generator, Amplifier, Power Supply and Vibration Controllers</li> <li>• Measurement &amp; Sensing Equipment: Accelerometers, Load Cells/ Force Sensors, Displacement sensors/ LVDTs, Sensors/PZT patches/accelerometers for the measurement of vibration field of powder flow</li> <li>• Data Acquisition and Processing: DAQ system, Oscilloscope/Data Logger, Software for Signal Processing, Workstation</li> <li>• Fluidizing blower/mini-compressor, air flow meter, heater, pressure gauge, temperature gauge, pipe/tube connections</li> <li>• Fluidizing pads, aeration nozzles of different types</li> <li>• Amendment to existing shear cells in Jenike tester</li> <li>• Transparent hoppers</li> <li>• High speed camera</li> </ul>	14000	12000		26000
2.	Fabrication (industrial scale development for validation) <ul style="list-style-type: none"> <li>• Industrial scale vibration and aeration system development optimized through laboratory scale work using the above mentioned items but in sufficient numbers and scale for industrial installation, testing and validation</li> </ul>			10000	10000
3	Manpower (salary/stipend for project staff) <ul style="list-style-type: none"> <li>• 1 Post Doc - Rs. 75000 per month for DEM/DEM-CFD simulation, modelling and site testing</li> <li>• 1 PhD student - Rs. 50000 per month for experimental, modelling and site testing</li> <li>• 1 Under-graduate intern - Rs. 12000 per month engineering design work</li> </ul>	19342	19342	19342	58026
4	Travel <ul style="list-style-type: none"> <li>• Industry/site having hoppers/silo to collect existing system data/problems/practices</li> <li>• Visit to local vendors for fabrication</li> <li>• Visit to IFPRI meetings, international and national conferences – registration and travel</li> </ul>	4000	6000	8000	18000

	<ul style="list-style-type: none"> <li>• Site visit for plant installation at industrial scale and testing/validation</li> </ul>				
5.	<b>Consumables and contingency</b> <ul style="list-style-type: none"> <li>• Purchase of powders</li> <li>• External power characterization – such as laser diffraction method, morphology etc.</li> <li>• Software upgradation/AMC</li> <li>• Stationary items</li> <li>• Tools and tackles for testing at site</li> <li>• Items of contingency/unforeseen nature</li> </ul>	2500	2500	2500	7500
6	<b>Institute overhead</b> 5% of project cost (sum of items 1 to 5)	1992	1992	1992	5976
	<b>Total (USD)</b>	<b>41834</b>	<b>41834</b>	<b>41834</b>	<b>125502</b>

## 12 Future scope

This proposal covers the effects of vibration and aeration on the power flow through thorough hoppers/silo. Future work will include application of the same to chute flow.

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## Annexure I: Literature Review

**Kollman and Thomas (2002):** This study examines how mechanical vibration affects the flow behavior of cohesive powders, particularly the impact of harmonic vibrations on shear forces and wall friction in fine powders. This research examines two typical vibration applications in industry: external vibrators, such as unbalanced motors or pneumatic vibrators on hopper walls, and internal vibrating hoppers, known as bin activators. A vibrating direct shear tester was developed to analyze vibration-induced powder flow, based on the design by Roberts and Scott (1978). The top half of the shear cell was vibrated with the base fixed in one of two test configurations, while the full shear cell, mounted on a vibrating plate, was vibrated in the other. Experimental results indicate that vibrations decrease the maximum shear force needed to initiate powder flow at a specific normal stress. Disabling vibration returns the shear force to unvibrated levels, indicating that vibration activates the powder. Shear stress during vibration correlates strongly with maximum vibration velocity, decreasing asymptotically as velocity increases. The internal friction angle of the powder is largely unaffected by vibration, while the unconfined yield strength decreases with higher vibration velocity. The relationship between wall shear stress and vibration velocity shows that as vibration velocity goes up, the wall friction angle goes down, indicating that mechanical vibration lowers both shear resistance and wall friction.

**Wassgren et al. (2002):** This work examines the effects of vertical vibration on the discharge pattern of granular materials from a wedge-shaped hopper through experimental methods and discrete element method (DEM) simulations. Two hopper designs were evaluated using 1.3 mm soda-lime glass beads, subjected to vertical vibration at frequencies of 5, 10, 20, 40, 60, and 80 Hz. Without vibration, the flow showed a funnel shape, with still areas near the sloped walls and active movement of particles in the middle. When vertical vibration was applied, especially at levels above 20 Hz, it created clear convection cells in the hopper, causing particles to move up along the walls and down in the middle. Surface waves emerged at specific vibration intensities, signifying flow instabilities. The mass discharge rate typically declined with higher vibration frequencies below 50 Hz; however, at 60 and 80 Hz, it was comparable to or slightly exceeded the non-vibrating condition. The discharge rate correlated more consistently with vibration velocity than with acceleration, indicating that the relative motion between the hopper and particles influences flow behavior. High-speed imaging in their study revealed that particle exit velocities exhibited sinusoidal variation throughout each vibration cycle, with phase lag resulting from frequency. At low frequencies and high accelerations, the hopper sometimes descended more rapidly than the exiting particles, leading to temporary material re-entry. DEM simulations confirmed that vibration frequency, amplitude, and wall friction significantly influence granular flow.

**Langston et al. (2009):** They examine how mechanical vibrations help improve and control the movement of sticky granular materials in wedge-shaped hoppers by using the Discrete Element Method (DEM) and continuum modeling. While continuum models are capable of simulating full-scale systems, they often rely on complex assumptions. DEM simulations, while computationally intensive, provide a clearer particle-level perspective. This study shows the complementary nature of the two techniques, with DEM results consistent with the Stress Arc theory in continuum mechanics. The effectiveness of vibration is significantly influenced by its placement in the hopper; vibrations too near the outlet or positioned high fail to reduce flow blockages adequately. A hopper with a small orifice permitted flow initiation through a limited region via vibration.

DEM simulations showed that when the hopper vibrates, the stress was steady at the vibrator, active above it, and expanded below it. Most simulations were 2D; however, 3D results corroborated similar trends, exhibiting enhanced cohesive behavior. The study emphasizes vibration characteristics: high-frequency, low-amplitude vibrations disrupt cohesive arches, while low-frequency, high-amplitude vibrations displace material.

**Dunst et al. (2018):** They investigate the impact of mechanical and ultrasonic vibrations on the flowability, transport, and dispersion of fine, cohesive powders. They utilized a vibratory platform to assess flowability by measuring the angle of repose. Experimental data showed that higher vertical vibration amplitude decreases the angle of repose, suggesting improved flowability. A critical amplitude induces heap dispersion. The relationship between angle of repose and acceleration is linear at 30–100 Hz, becoming non-linear at higher frequencies due to increased damping from interparticle friction. Ultrasonic vibrations (>100 Hz) penetrate the powder bed minimally but are effective for small amounts of fine powders. The study demonstrates that vibrations decrease the effective coefficient of friction between powder particles and surfaces. Friction can help things move for short periods, depending on the direction of the vibrations (up and down, side to side, or at an angle), which reduces the overall resistance. Radial and transversal vibrations exhibit greater efficiency than longitudinal vibrations. A vibratory transport system utilizing coordinated axial (low-frequency) and radial (ultrasonic) vibrations was developed. Vibration amplitude and pulse width were adjusted to control powder mass flow and velocity. Reversing the flow direction is possible by shifting the phase between axial and radial excitation by 180°. The system effectively transported ultrafine powders (<1 µm) up slopes (>10°), minimizing residue through friction reduction. Ultrasonic vibration effectively facilitates powder deagglomeration and dispersion via direct sonotrode contact or airborne ultrasonic fields. Ultrasound facilitates uniform blending of cohesive powders, such as flour and cocoa, by disaggregating agglomerates.

**Jafari and others (2018)** study how localized mechanical vibration affects how granular materials move in silos, especially when they get stuck. The experiments used quasi-spherical mineral aggregates that were 4 to 10 mm wide in a clear PMMA silo that had removable hoppers and a fast-opening outlet gate. A vibrator with an unbalanced rotating mass was affixed to the silo wall at three heights (50 mm, 100 mm, and 150 mm) and operated at four frequencies: 15.08 Hz, 25.08 Hz, 27.05 Hz, and 29.16 Hz. Vibration characteristics were assessed with a vibrometer, and mass flow was measured using a high-precision load cell. The results indicated that when the silo discharged freely, vibration had minimal effect on flow rates, suggesting it is unnecessary under optimal conditions. Under jammed conditions, vibration notably influenced flow behavior based on vibrator location and frequency. Vibrators near the outlet effectively prevented jamming and ensured continuous discharge, with average flow times of approximately 62 seconds. Increasing the vibrator's height led to more flow interruptions and longer discharge times, occasionally causing complete blockage. Using higher vibration frequencies helped prevent jamming, even when the vibrator wasn't in the best position, and better flow was observed at 29.16 Hz compared to lower frequencies. The findings suggest that the vibrator's proximity to the outlet is crucial for preventing jamming, as lower placement directs energy effectively to disrupt arching. Additionally, frequency improves the vibrator's usefulness, especially when there are limitations on placement.

**Zhu et al. (2020):** They examine the discharge of cohesive powders from a hopper with square-wave pulsated airflow to address arching and flowability issues common in fine, cohesive materials. The experimental setup features a lab-scale silo with pulsation-enabled aeration via solenoid-controlled airflow, tested at frequencies of 0 to 50 Hz and different amplitudes. Studied materials include pulverized coal, calcium carbonate (cohesive), and glass beads (non-cohesive). Pulsated aeration markedly improves discharge performance for cohesive powders, reducing the minimum aeration rate by over 50% relative to continuous flow. Pulverized coal exhibited discharge at gas flow rates of 0.75 L/min with pulsation, compared to 2.0 L/min without. Discharge rates increased by approximately 20% with high-frequency pulsation (>1 Hz), resulting in smoother flow and diminished rate fluctuations. The study indicates that low-frequency pulsation (<1 Hz) causes intermittent discharge, whereas higher frequencies (>1 Hz) produce continuous, stable flow. Pulsation enhanced uniform aeration by disrupting aggregate structures and reducing channel formation among agglomerates. The estimated aggregate size under pulsation conditions, based on the analysis of Ergun pressure drop and cohesive strength models, demonstrated consistency and a reduction in size with increased pulsation. Pulsated aeration enhances cohesive powders but degrades flow in free-flowing materials, such as glass beads, due to induced instability. The findings directly impact powder-handling industries, particularly where cohesive materials obstruct standard hopper discharge operations.

**Kawahara et al. (2021):** This study looks at how fine cohesive powders are released from a special hopper that has a semi-conical shape and uses a system with a rubber air spring. The system uses a flexible inner container that expands and contracts regularly, controlled by air movements, to prevent clumping and blockages when the powder is released. Experiments used fly ash (average particle size about 22.4  $\mu\text{m}$ ) to study factors like the height of the air injection port, air pressure, and how long the valve is open or closed. The position of the air injection port significantly affects discharge performance. Optimal flow occurred when the port was positioned approximately 40 mm above the discharge port, effectively disrupting arches and ensuring consistent flow. The oscillating air motion of the flexible membrane caused pressure fluctuations in the powder bed, facilitating the collapse of flow obstructions. Pressure oscillation amplitude and persistence in the airtight cavity correlated with powder flow continuity. Longer valve open times resulted in pressure amplitudes nearing an upper limit ( $\sim 125$  Pa), signifying the rubber film's expansion threshold. Flow visualization showed the formation of air voids and movement upward when the arch broke down, supporting the mechanism that flow improves due to the instability of the powder bed. This study presents a low-mechanical-stress solution for cohesive powder handling in process industries.

**Hartig et al. (2022)** developed a model that combines CFD and DEM to study how powder acts in vibrating conveyors with air, particularly in continuous vibrating reactors for atomic layer deposition (CVR-ALD). Simulations utilized comprehensive material characterization of four powders (20–250  $\mu\text{m}$ ), focusing on particle size distribution, sphericity, and surface cohesion properties. Vibratory convection in fine powders results from the interaction of gas drag, vibration-induced forces, and van der Waals cohesion. The study shows that when the throw numbers are low ( $\Gamma = 0.25\text{--}0.50$ ), fine cohesive powders move in a hopping manner because they occasionally become fluid-like during the pulling-back phase. Coarser powders, exhibiting higher minimum fluidization velocities, primarily experience shear-induced transport without liftoff. Simulations show that increasing the gas speed below fluidization can help lift the powder by supporting the particle bed, but too much stickiness makes it harder to lift and slows down movement.

Coordination number analysis and voidage profiles reveal that cohesive powders stay tightly packed with little movement inside, while non-cohesive or weakly cohesive powders often rearrange their particles. The model includes how particles interact with each other and with the walls using Hamaker constants and looks at granular Bond numbers to measure cohesive forces. Cohesion-induced convection suppression occurred when Bond numbers surpassed critical thresholds, particularly at low vibration intensities. Experimental validation demonstrated a high correlation between simulated and measured convection velocities. This study highlights how important the design of the porous baseplate and the forces that hold particles together are for modeling aerated vibratory conveyors. It helps to understand how particles move, which is important for handling fine powders in modern processing systems.

## Annexure II: Short CV of Investigators

**Principal Investigator Dr. S.S.Mallick** is a Professor in the Department of Mechanical Engineering, Thapar Institute of Engineering & Technology (TIET). After completing his PhD in powder handling from the University of Wollongong Australia, Dr.Mallick has set-up Powder and Bulk Solids Handling Research laboratory at TIET with funding from Government of India and subsequently from major industries such as NTPC. His laboratory contains pneumatic pressure and vacuum conveying pilot plant, powder flow/shear tester, segregation tester, angle of repose tester, loose poured bulk and tap density testers, chute tester, solar PV panel dust cleaning rig, hopper rigs, fluidization-deaeration testers, Discrete Element Simulation (DEM) and CFD license and multiple high power computing facility. Dr. Mallick has tested/conveyed/designed about 150 different powders including fly ash, cement, pharmaceutical, food, paint, metal powder etc. Dr. Mallick has supervised 8 PhD and 30 Masters level students in powder and bulk solids handling. Dr. Mallick has executed 40 research and industrial consultancy projects. He has been the Associate Editor of Particulate Science & Technology, Taylor & Francis (2016-2021). Dr. Mallick has organized 4 international conferences and 8 professional development courses and delivered numerous invited lectures in industry.

**Co-Principal Investigator Dr. Ashish Purohit** is Associate Professor in Mechanical Engineering Department at Thapar Institute of Engineering & Technology, India. He received his PhD (2010-15) and Masters degree in Machine Design (2006-06) from the Department of Mechanical Engineering, Indian Institute of Technology Delhi (IITD) and Bachelors from Govt. Engineering College, Ujjain in 2001. About his exposure to industries, Dr. Ashish has worked in the Automobile sector as designer at Engineering Research Center (ERC) of Tata Motors Ltd. (2008-2010), and also as a Scientist at Vikram Sarabhai Space center, (ISRO), India 2005-06. During his academic tenure since 2015, he has supervised two Doctoral Thesis and more than 15 Masters Thesis. His area of work is Mechanical Vibration, Rotor Fault Detection, Flow-Induced Vibration with the focus of understanding the effect of different excitations on vibration propagation and system response using both experimental and simulation investigations. He is also working for particle flow simulation and its behaviour under dynamic loadings. He has published more than 20 research papers in various peer reviewed journals and international conferences. He has completed a sponsored project about performance enhancement of piezoelectric energy harvesters under flow of 24 Lacs funded from the Indian government. Currently, he is working on a research project worth 1.7 cr about biomass utilization in power plants where in simulation of particle fracture, flow of particles, vibration of bulk solids etc. are some of the important research objectives.

**Co-Principal Investigator Dr. Pankaj Kumar** serves as an assistant professor in the Department of Mechanical Engineering at Thapar Institute of Engineering and Technology, Patiala, Punjab. He is an active researcher focusing on wave mechanics, structural dynamics, and mechanical vibrations, with a specific emphasis on ultrasonic-based structural health monitoring and non-destructive evaluation methods. His present research investigates the utilization of progressive waves and vibrations for the precise manipulation, transportation, and segregation of granular materials. Dr. Kumar obtained his Ph.D. in Mechanical Engineering from the Indian Institute of Technology (IIT) Kharagpur in 2020 and his Masters in Engineering Mechanics from the Department of Applied Mechanics, IIT Delhi, in 2012. Upon obtaining his doctoral degree, he became a faculty member at Thapar Institute in August 2020. Dr. Kumar possesses nearly four years of post-Ph.D. academic and research experience, establishing a robust foundation in experimental

methodologies, vibration analysis, and wave propagation in solids. He has published several research articles in esteemed journals and possesses a patent in the domain. He possesses the knowledge and background needed for successful completion of the objectives laid out in this proposal.