

Understanding formation and growth mechanism of thick powder layers on process surfaces

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Summary

Deposition of powders on the surface of process equipment (process surface) is very common phenomena across industries. While at the initial stage of the layer formation is due to very loosely adhered particles on the process surface, under the influence of the prevailing environmental and process condition, the layer becomes thick and immobile which creates problems in chutes, silos, pneumatic conveying lines, milling machines, dryers, mixers, furnaces etc. Though the phenomena is very well known across industries, there exists lack of scientific knowledge to understand the formation mechanisms of the thin powder layer (“nucleation”) and its growth or death under various process and environmental conditions. In this proposal, it is proposed to explore the underlying scientific knowledge which dictates the formation and growth of the undesired powder layers which creates severe problems in the powder handling industries.

The study aims to correlate various particle properties (1) and powder bulk properties (2) under different environmental conditions (3) and their interaction with equipment surface (4) during various processes (5) of different consolidations (6). The effort will establish the formation and growth kinetics of powder layer on the equipment surface. The work will help the powder industries to identify the critical parameters in the powder ‘horoscope’ (shown in Figure 1) and predict the powder layer formation on processing equipment at the different process and environmental condition. The study has also an enormous implication to solar energy industries where dust deposition on the solar panel reduces significant energy production. The results of the study will help industries to take appropriate cleaning strategy to reduce particle deposition on the process equipment as well as solar panels.

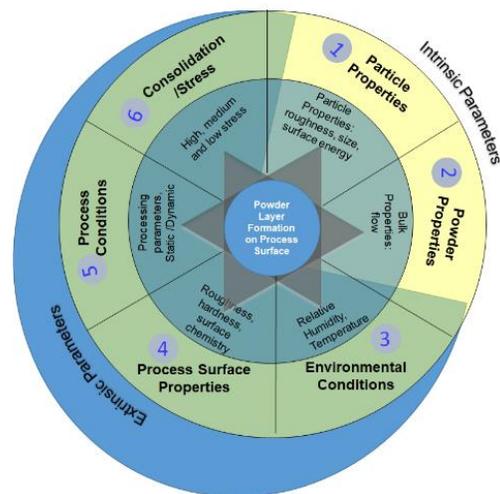


Figure 1: Powder 'horoscope'

1. Background of the proposed research

Powders form an important component in various industries like pharmaceutical, cement, food, minerals, fertilizers, paints, dyes, catalysts, additive manufacturing industries etc. Majority of these industries process different fine powders which often belong to group C powder (Geldart, 1973). The various unit operations in the powder industries are mixing, agglomeration, drying, comminution, fluidization, granulation, separation etc. along with its storage (silos, cans, bags) and transport (feeders, hoppers, conveyors). The powder processing through process equipment results deposition of fine particles on the equipment surface (process surface) due to strong adhesion between process surface and particle surface under the prevailing consolidation, process and environment conditions (categories here as extrinsic parameter such as RH, T, consolidation or stress, static or dynamic condition etc.). These adhered particles on the process surface grow over time (Figure 2) and create the problem in powder operation.

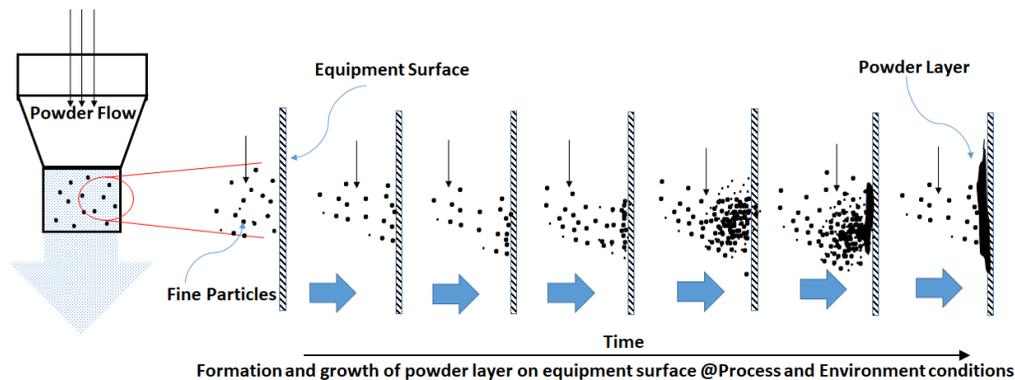


Figure 2: Schematic of powder layer formation (probable mechanism)

The phenomena influence by various physicochemical properties of particles (such as particle size and its distribution, shape, surface area, density, surface roughness, surface chemical groups, surface charge and surface energy) and bulk powders (flow, compressibility, packing) (Ghoroi et al., 2013; Shah et al. 2017) which are categories here as intrinsic parameters. Both intrinsic and extrinsic parameters (detail parameters of powder horoscope shown in Figure 3) influence the inter-particle interaction forces which ultimately affects the adhesion or sticking property of the particles among themselves (form the agglomerates) and on the process surface as shown in Figure 2. The inter-particle interaction forces like van der Waals forces, electrostatic force, capillary force and solid bridge force affect the powder bulk properties like powder flow, compaction and particle interaction with process surface. Though the attractive inter-particle interaction is desired for specific application such as granulation, roll compaction, the coating of particle, it is undesirable during handling or processing of highly cohesive powders which causes unwanted processing problems and losses such as powder build-up on the process surface, loss of powders, product quality. Though there are few studies on particle properties to bulk powder properties (two intrinsic properties: Region 1 → Region 2 in the powder horoscope) (Shah et al. 2017), but their influence on powder layer formation on process surface is mostly unavailable in the literature.

In addition to the inter-particle forces between particles, there are also different stresses involved namely, tensile stress (pulling force), compressive stress (pushing force) and shear stress (force

acting parallel to the motion) during powder handling and processing operations. Friction could become dominant inter-particle interaction in powder flow, especially in dry conditions (Castellanos, 2005) referred as dry friction (coefficient of friction, μ). Sometimes, this friction also generate the stick-slip type of friction which is highly undesirable phenomena in many powder handling industries (Roberts and Wensrich, 2002).

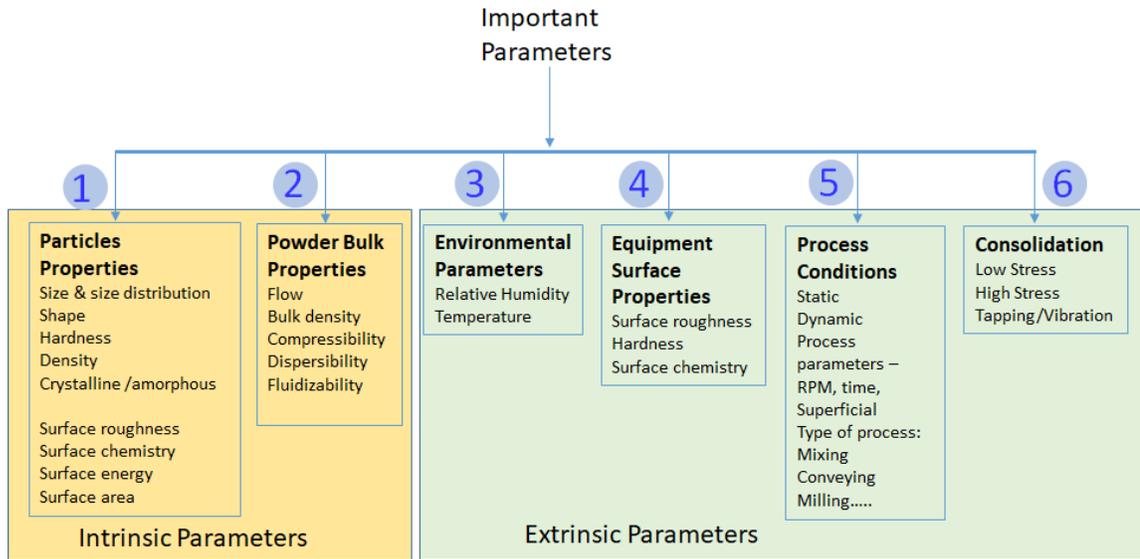


Figure 3: Details parameters which influences the powder layer formation in process surface

The extrinsic properties such as atmospheric humidity greatly affect powder materials due to the presence of unbound moisture, which is available for chemical or physical interactions (Karde & Ghoroi 2015; Bravo-Osuna et al., 2007; Faqih et al., 2007; Zografis G., 1988). Moreover, these interactions are also influenced by the frictional force between particles and between particles and contacting equipment surface. Presence of humidity, temperature, stress and the type of the process increases the interactions which are undesirable during transport, storage and in the feed systems. Humidity can also influence the van der Waals forces. Coelho and Harnby (Coelho and Harnby, 1978) found that the van der Waals forces are strengthened by adsorbed moisture because the added thickness of moisture layer decreases inter-particle distance by increasing the apparent diameter of the particle. It is well known that at the higher relative humidity (RH), capillary forces may contribute largely to the inter-particle adhesion forces. However, the actual impact of humidity on adhesion may depend on number of factors like particle size, shape, roughness, material properties like elasticity modulus, hardness along with packing or consolidation state of powders and surface properties of the process surface (Butt, 2008; Cleaver and Tyrrell, 2004; Farshchi-tabrizi et al., 2006; Paajanen et al., 2006). Also, the electrostatic interactions decrease in presence of moisture due to the dissipation of charges through conductive properties of water molecules. In some cases, the moisture adsorbed on the surface could lead to increase in flowability owing to the lubrication effect of the moisture film and as a consequent reduction in inter-particle friction and mechanical interlocking (Coelho and Harnby, 1978; Crouter and Briens, 2014). The resultant effect may be either an increase in the inter-particle capillary force at high humidity conditions or increase in other forces such as friction, van

der Waals and electrostatic at low humidity (Emery et al., 2009; Rowley and Mackin, 2003), all of which could create complications in powder processing or handling. However, not much work is there on particles interactions on process surfaces under these external variables.

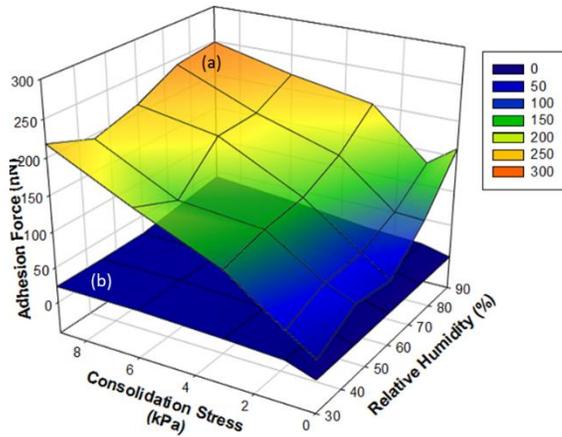


Figure 4. 3D plot depicting experimental inter-particle adhesion forces under varying humidity and consolidation for (a) as received or uncoated and (b) nano-silica coated corn starch powders

In addition, the compressive stresses in powder bed influence powder behavior to a great extent (Valverde et al., 1998), especially in cases when the powder is stored in silos, hoppers etc. These compressive forces developed during storage, handling or processing are an important consideration while determining particle adhesion. Depending upon the industrial processes involved, these compressive stresses exerted could vary from very high (during compaction) to lower values (during mixing, separation, dispersion, fluidization). Further, the introduction of humidity could make the situation much more complex. As such, the typical effect of humidity on powder bulk behavior is familiar to powder flow community (Crouter and Briens, 2014; Emery et al., 2009; Mollan and Celik, 1995). However,

a combined effect of humidity and applied consolidation on powder behavior under different temperature is not studied well. In such cases, the estimation of total adhesion forces in powders exposed to different RH conditions at varying compressive stresses can provide a much better understanding of powder flow for different applications and its interaction with process surface. Our recent investigation of humidity influenced frictional behavior of corn starch powder under varying consolidation stress and its effect on the bulk behavior within the relative humidity conditions $\leq 60\%$ (Karde & Ghoroi 2015) indicates that for as received powders at low consolidation stress, the contribution from the inter-particle capillary forces is greater to the total adhesion forces (Figure 4). However, at higher consolidation load, other contact forces become dominant. Humidity and consolidation induced contact deformation in particles led to increasing in total inter-particle adhesion forces. From our preceding work, it is clear that the powders display (corn starch as model powder) a tendency of exhibiting increased cohesivity owing the unusual frictional behaviour at lower RH conditions. However, detail understanding requires comprehensive investigation on the subject. In fact, literature on the powder layer formation on process surface is not there.

2. Motivation

The fine powder deposition on the process equipment is very common phenomena observed in the powder-based manufacturing process. This is mainly due to sticking of particles on the process surface under process and environmental condition. The phenomena results powder build up, powder loss and also influences the product quality. Moreover, it has a huge implication in the solar energy production. Deposition of dust particle can contribute about 17 to 25% energy

production (Mike & Ghoroi 2017 et al. 2017) which can cost India 1 billion USD per annum for projected 100 GW solar plan by 2022. Though powder deposition on the surface is very critical across industries, there exists scientific knowledge gap in the powder community except for few studies on fine particles adhesion on electronics (Ranade 1987). The proposal is intended to study this important issue and generate scientific knowledge on formation mechanism and growth kinetics of powder layer on the process surface.

The research questions

- What are the critical parameters responsible for powder adherence and powder layer formation?
- How does the powder layer grows over process surface?
- What are the parameters which help to destroy or grow the layer?
- What is the correlation among different parameters which dictate the nucleation and growth mechanism of the powder layer growth?
- How to validate the plant scale powder layer from the laboratory scale study?
- Does the mechanism is true for all the particles? What is the influence on particle size and their surface characteristics?
- What must it (powder layering) is influenced by extrinsic parameters?

3. Objectives

- Identify the critical parameters for powder layer formation (nucleation) and growth
- Establish mechanism of the layer deposition
- Establish model that will predict the powder layer formation irrespective of the scale
- Training to students and personnel from industry through labs, course and workshop

4. Methodology

Understanding powder behavior involves large number particle and powder properties which makes it difficult to analyze the powder system. In fact, unlike their counterpart (fluid system), the powder system is inherently complex. The proposed research is plan to investigate the different interactions using powder 'horoscope' involving various binary, ternary and quaternary interactions among six groups of parameters described through six specific regions (particle, powder, environment, process surface, process conditions and nature of consolidation in Figure 1. For example, particle interaction with process surface (wall) can be explore by studying the various parameters of region 1 (R1) and region 4 (R4) in the powder horoscope. Thus, a few binary and ternary interaction studies are planned (as in the Table 1). Similarly, several binary, ternary and quaternary interactions are planned for the project to understand the powder layer formation and growth mechanism.

Table 1: Various interactions among different components in the powder horoscope

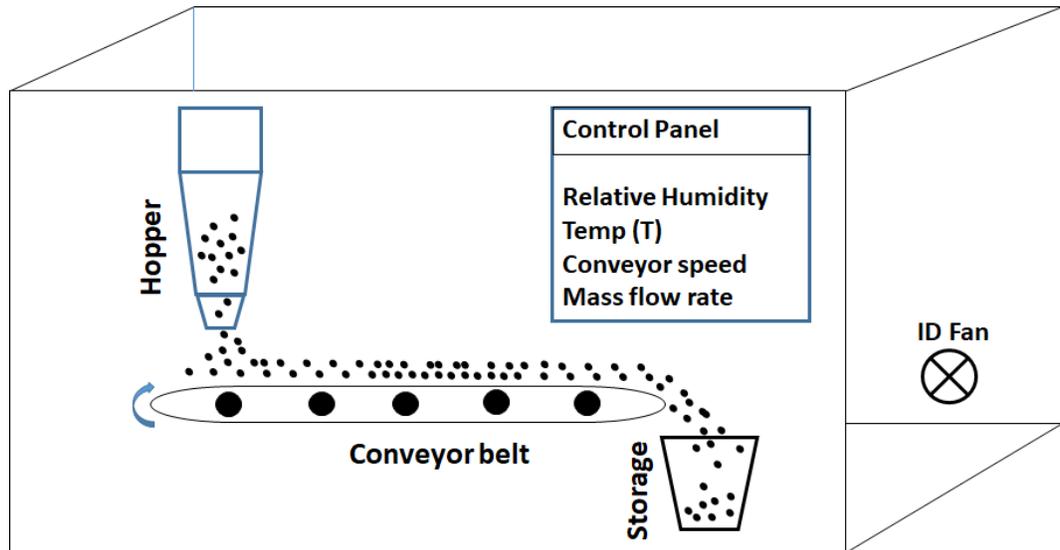
No	Symbol	Interactions	Different phenomena study based on the different regions of powder horoscope
Binary interactions between two different regions in the powder horoscope			
1	A-14	R1 – R4	Particle – wall interactions: particle parameters vs. process surface parameters
2	A-25	R2 – R5	Powder behavior under process conditions: Mixing, fluidiation, milling etc.
3	A-36X	R3 – R6	Environmental conditions on consolidation / stress
4	B-12	R1 – R2	Particle properties to powder properties
5	B-23	R2 – R3	Powder properties under environment conditions
6	B-34X	R3 – R4	Influence of environment on process surface
7	B-45X	R4 – R5	Process condition on equipment surface parameters
8	B-56X	R5 – R6	Process condition and consolidation / stress
Ternary interactions among three different regions in the powder horoscope			
9	C-135	R1 – R3 – R5	Particle behavior under process conditions at various environmental condition
10	C-246	R2 – R4 – R6	Powder bulk properties at different consolidation under process surfaces
11	D-123	R1 – R2 – R3	Particle and powder properties on environmental conditions
12	D-234	R2 – R3 – R4	Powder bulk interaction with process surface under environmental conditions
13	D-345X	R3 – R4 – R5	Process condition on process surface under environmental condition
14	D-456X	R4 – R5 – R6	Process condition on process surface at different consolidation
15	E-612	R6 – R1 – R2	Particle properties when powder under consolidation
16	E-561	R5 – R6 – R1	Particle properties under consolidation at various process conditions
Quaternary interactions among four different regions in the powder horoscope			
17	F-1345	R1-R3-R4-R5	Particles under different environmental conditions, process surfaces and process conditions
18	F-2456	R2-R4-R5-R6	Powder behavior in different processes involving different surfaces and consolidations
19	F-3561	R3-R5-R6-R1	Particle in different process condition and consolidation under different environment condition
20	F-4612	R4-R6-R1-R2	In presence process surface how particles and powder behaves under consolidation
21	F5123	R5-R1-R2-R3	In process condition how particle behaves under different environment conditions
22	F-6234	R6-R2-R3-R4	Under consolidation how powder behaves in contact with process surfaces under different environmental conditions

The symbol end with 'X' (A-36X, B-34X, B-45X, B-56X, D-345X, D-456X) corresponds to the interaction where either particles (R1) or powders (R2) is not there. So they will not be considered for this study. However, their influence and information are important in other aspects of scientific investigation.

5. Scope and experimental plan

- Time scale of the study: 3 years
- Model powders: one hydrophobic, one hydrophilic, one spherical and one cylindrical shaped particle
- Size range: 5 microns to <120 microns powders
- Models process surface – Stainless Steel, rubber, plastic and glass surface
- Environmental conditions: RH variation from 30 to 90% and temperature variation from 10°C to 65°C
- Consolidation: zero to 15 kPa
- Process conditions: Some of the experiments to be considered in static condition (storage vessel) and some are in dynamic condition (mixing, conveying, milling)

- Parametric variations to be studied: as per the table 1 for each type of powder and each type of process surface at several environment conditions and consolidations.
- Some experiments will be carried out to study the importance of various extrinsic parameters on powder layer formation. Similarly some experiments will be planned to understand the correlation among intrinsic parameters only (particle to bulk scale relation: R1 & R2). Results from both the type of experiments will be compared to find any parametric correlation with the various extrinsic and intrinsic parameters.
- While thickness of the powder layer measurement will be planned for experiments in V-blender, ball mill, fluid energy mill and the turbula mixture in the lab in the room condition at different time of the year to capture the various environmental conditions, there will be dedicated experiments in the fabricated instrument to measure the powder layer deposition on the hopper, conveyor belt and storage device under controlled environment as shown in the schematic experimental setup in the figure 5.
- All the data will be compiled to generate the mechanism of the powder layer formation and growth kinetics for different powder for different process and environment conditions.
- Some of the experimental finding will be compared with the plant data available from Indian industries or industry members from IFPRI



Controlled chamber to study the powder layer deposition on process surface

Figure 5: Controlled experiments to study the powder layer deposition in hopper, conveyor belt and the storage vessel.

6. Timeline and Experimental plan

No	WP	6	12	18	24	30	36
1	WP1	█					
2	WP2	█					
3	WP3	█	█				
4	WP4	█	█				
5	WP5	█	█				
6	WP6		█	█			
7	WP7		█	█	█		
8	WP8		█	█	█	█	
9	WP9			█	█	█	
10	WP10				█	█	
11	WP11					█	█
12	WP12					█	█
13	WP13						█
14	WP14						█

Table 2: Description of the work packages (WP)

No	WP	Description of the various work packages
1	WP1	Hiring Manpower
2	WP2	Literature
3	WP3	Procuring instruments
4	WP4	Detail physicochemical characterization of the model particles, powders and process surfaces at room condition
5	WP5	Detail physicochemical characterization of the model powders and process surfaces at controlled environment (3 RH and 3 temperatures covering Indian weather conditions)
6	WP6	Measuring particle – process surface interactions in terms of friction coefficient, sticking coefficient, adhesion force measurement
7	WP7	Powder processing in flow through hopper, different mixing, milling devices in the lab and measure the deposited powder layer thickness measurement for given room RH and T
8	WP8	Study the interactions as per Table 1
9	WP9	Experimental set up fabrication and conducting studies in the fabricated instruments and layer thickness determination
10	WP10	Analyse growth kinetics of powder layer formation in different experiments

11	WP11	Correlate growth kinetics of powder layer with the powder and particle properties and other extrinsic variables
12	WP12	Formulate prediction tool for powder layer formation
13	WP13	Making reports of the research findings, publications
14	WP14	Knowledge dissemination to Indian industries and academia through joint workshop of IITGN & IFPRI

7. **Yearly milestone** (An outline of what will be accomplished in each of the three years)

Year 1

- Complete recruitment of the manpower, install the instrument
- Complete details characterization of particle, powder and process surfaces under different process and environment conditions

Year 2

- Complete the fabricate of the experimental set up and perform half of the intended experiments
- Complete the study of various binary, ternary and quaternary interactions described in table 1
- Complete the experiments on flow through hopper, different mixing, milling devices in the lab and measure the deposited powder layer thickness for given room RH and T
- Complete the interactions as per Table 1

Year 3

- Complete the controlled experiments in the fabricated experimental set up
- Complete the analyse of all the data
- Establish the formation mechanism and growth kinetics
- Complete the report and workshop for dissemination of the knowledge

8. **Critical unknowns that may influence the direction/outcome of the project):**

- Not getting proper manpower in time
- Getting multiple varieties of industrial powders in time
- Attrition of trained manpower
- Instrument breakdown

9. Budget

Table 1: Budget in USD for three years

	Items	Year 1	Year 2	Year 3	Total
A	Equipment/Fabrication	32,394	7,042	0	39,437
B	Consumables	2,817	2,817	2,817	8,451
C	Salary	13,183	13,183	13,183	39,549
D	Travel	4,225	4,225	4,225	12,676
E	Workshop	0	0	4,225	4,225
F	Total (A+B+C+D+E)	52,620	27,268	24,451	104,338
G	Overhead (20% of F)	10,524	5,454	4,890	20,868
	Total (E+F)	63,144	32,721	29,341	125,206

Total budget USD 125, 206 (Year 1 USD 63,144, Year 2 USD 32,721 and Year 3 USD 29,341)

10. How this project could leverage into existing programs

In spite of production of large quantities of fine and ultra-fine powders in industries and well know handling problem across industries, science and engineering of handling this class of materials are often ignored or underestimated. In fact, the subject is seldom taught in University curriculum except for very few Universities in the world. Even a passing reference to this important subject remains unheard during the whole span of undergraduate /postgraduate education. Powder processing industries are mostly dependent on the experience of the workforce who learn the art by handling fine powder in day-to-day plant operations. The Legacy continues without much progress in fundamental understanding in the area. To fill this gap, research on fine powder got some momentum around the world in the last few decades. Along with the IFPRI's initiative and Engineering Research Center for Particle Science and Technology by NSF at University of Florida (1994), the National Special Super Fine Powder Engineering Research Center of China is more recent initiative of China in 2005. However, in India, it is yet to be appreciated. India being a major producer of pharmaceutical powders and prominent player in food, cosmetic and fine chemicals etc, this becomes more important. Presently there is no dedicated research lab in the country in this area. A basic understanding of science and engineering of fine powders can minimize several problems in many industries and help the industry to improve existing operations and quality of product. Thus, there is a gap in the country for proper education, training and research on Fine Powder which is prerequisite for further advancement of powder handling industries. Keeping this in mind, we have created a state-of-art Fine Powder Research Lab which is providing related education, training and research in India.

As we are located in country's industrial hub, there is enormous opportunity to connect our research with industry. Along with the planned research, training through workshops/symposiums, summer research and short term research program is very much active. About 15 students from other Universities trained in our lab on fine powder research. Also, we have introduced a course on "Particulate Solid Processing & Surface Engineering" for senior undergraduate and postgraduate

students at IITGN. The course have considerable theoretical component and extensive hands on experience on handling fine powders in the lab scale. Several IITGN students have benefited from the course. In addition, we have managed to write several research proposals for funding and attracted 7 PhD students and 7 M.Tech students along with several Junior Research Fellows (JRF) to work on various aspects of particles and powders. During the last few years, we have also established several industrial collaborations.

Major research focus in our research group is on understanding fine and cohesive dry powder (Geldart's Group C) and its behavior in static and dynamic conditions; Influence of humidity on powder flow; Surface engineering of fine particle (using nano-particle, plasma processing, lithography & chemical methods) for improved dry powder processing – mainly improving flow & packing; surface wetting and super-hydrophobic/ Hydrophilic powders etc.

These ongoing activities in our research group is very much in-line with the proposed project and the initiatives of IFPRI to spread the powder research. The proposed project has direct bearing to strengthen our existing program (both to strengthen the research and curriculum) on fine particles and powders. In addition, through the proposed project, our research group and IFPRI together can arrange knowledge sharing sessions for Indian academics and industries which will be a huge benefit to fine powder research in India.

11. IFPRI members support the program through following provisions

In the proposed project from IFPRI can help us to strengthen our effort on Fine Particle Research in India. There are multiple ways where IFPRI can help us where Indian scientists and engineers can be benefited. Also, IFPRI members can explore the various powder based Indian industries such as pharmaceuticals, food, cement, cosmetics etc. Thus, there are mutual benefit to float the proposed project in IIT Gandhinagar. It is more so because IITGN is strategically located in the Industrial hub of India. In the vicinity of IITGN, there are several clusters of industries which are handling fine powders in day-to-day basis. IFPRI members can help us by

- a. Providing model powders
- b. Training on few unknown test methods which can be extended to industry person
- c. Sharing their experience to students
- d. Sharing the experience to other Indian academics and Industries through workshop and hands-on-training
- e. Establishing the relationship with Indian Industries and encourage them to contribute in IFPRI

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