Research Gaps in Powder Flow: Purpose-Driven Particle Scale Product Design to Solve Process Issues

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In the 1960's the concept of solids flow design by applying continuum soil mechanic first principles to the geometries associated with typical handling systems was born. The original intent was to be able to predict the stress and solids loads in process equipment. It soon became evident that the infant theory could help engineers define how solids flow through a process vessel by adding a flow rule to the theory, thereby allowing for prediction of velocities and velocity profiles in these process vessels. So, terms such as mass-flow, funnel-flow, flow-no-flow criteria, limiting flow rate, yield locus (a collection of points that describes a limiting behavior namely yield) were coined. All of these are limit driven calculations which address the following questions:

Given the wall friction angle, hopper slope, and effective angle of friction – what is the flattest angle of a cone that will allow flow at the walls? Given the bulk density, permeability, wall friction angle and process geometry – what is the limit of the flow rate leaving the system for material in a fully deaerated condition? Given the unconfined yield strength and bulk density – what is the smallest opening that will still prevent an arch to form at the outlet of a process vessel?

Limit analysis is a wonderful tool in defining the limit of what can be done, but it does not give a rich description of the details of flow. Often it is the details of the flow, not the limiting analysis, that help engineers to create a purpose-driven design. For example, if I want to design a process to solve a segregation problem, I need to know more than just the limit of mass-flow versus funnel-flow. I need to know the velocity profile, how that velocity profile might interact with particles making up the bulk and what the overall effect of placing a bulk material with a given particle scale segregation behavior might have on how these particles enter and exit the handling system.

As a practicing engineer, I need a certain content uniformity to exit the process at all times and I, therefore, need to understand how to design my vessel to accomplish this task. My metric for success is that 95% of the material passing through my process must be within a given concentration limit and, perhaps, within a given density bound. It stands to reason that any theories I use, or property measurements I make, must be able to relate to content uniformity from a theoretical point of view. This is purpose-driven design, not limit-driven design. This is the goal of the credible researcher and at the crux of furthering our understanding of processes that handle powders and powder mixtures.

Current design follows this logic path. I have a segregation issue so, logically, I need mass-flow to assure everything moves when I empty the process vessel. So, let me go through mass-flow limit analysis and design my hopper to induce mass-flow and maybe add a safety factor and make the hopper a little steeper, just in case. In this example, I have designed with best practices. But, I still have no scientific basis that the design will work, other than optimism because almost every time I have done that in the past it worked.

But, what if I – as the engineer – could use wall friction angles, effective internal friction angles, hopper shape, and the segregation profile, and relate these to content uniformity leaving the vessel in some general way? It would then be possible for me to define or even plot not only the limit equation defining mass-flow / funnel-flow, but I could superimpose on top of this a contour plot of content uniformity – and now I can directly choose a hopper shape and a target wall friction angle to give me the content uniformity I need in a given process geometry with a given segregation characteristic. I have now designed the handling system with a purpose. This approach can also be done if I have a process needing the assurance that the time spent in the process is within a given range of residence times. My metric in that case would be 95% of all particles passing through the handling system need to be within 15% of the average residence time of the material in the bin. So, I could utilize the theories at hand with the key property measurements and process description, and compute the residence time divided by the average residence time to give an age factor for the process and super impose that data over the limiting plots we are so very familiar with. Now I can relate the material properties to the key parameters of interest for the design – namely the age factor in the handling system.

This is all fine for the engineer. However, at some point the engineer is going to approach the formulator and say: "Nothing we can get from the vendors will work in the system. I need you to make a new material that will work in my system. It needs to have this prescribed wall friction angle, this prescribed cohesive value, and this prescribed segregation tendency. Please make this for me." The formulator must now design the product with a purpose in mind. But, she does not have a roadmap of how to change particle size, particle shape, PSD, and perhaps particle surface adhesion to accomplish the purpose. There are even fewer theories available to relate particle scale properties to bulk scale behavior. But, as we enter the era of design-with-a-purpose, we must discover the theories that build the bridge between the particle scale world and the bulk world. One thing which we know for sure is that often we cannot transition directly from the particle scale world to the process world. It is like building a house. The clay must first be made into bricks, and bricks put in place to make the house.

So, with that in mind we will consider the following 3 questions in this presentation:

1. Current handling system design relies heavily on the radial stress theory which contains a series of simplifications. So, are there any additions to the theory that will extend the theory to cover more industrial situations? Can we express the results of using that theory in such a way that we relate the theory to engineering metrics that the engineer will use to design his process? Can we make it easy for him?
2. There are limited theories that relate bulk flow properties to particle scale models. So, can we define a set of rules that can take particle size, particle shape, particle size distributions, surface adhesions and environmental conditions and predict key bulk properties that, in turn, can be used to describe process behavior? What does that roadmap look like?
3. Some things we measure, such as segregation tendencies, are about how the set of particles interact with the velocity and velocity profiles in the systems. However, these types of variables are also influenced by bulk scale properties such as fluidization and cohesion (i.e. the system is convoluted such that changing the particle size changes the segregation and changes the cohesion which changes the segregation and so forth). So, can we build the bridge between the influence of bulk scale properties and the particle scale properties to remove this convolution problem? What are the key influences we must include in building this knowledge bridge?