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Engineering: On the Compaction of Particulate Materials, Like Granola, Etc., Part II

This column continues my discussion begun in the July-August 2011 issue of *Cereal Foods World*. In that column, I described some of the issues associated with the process of compacting particulate materials and briefly described the physics involved. In this column, I will review the first step in the process—the hopper that feeds the pair of rolls that create the initial sheet of material. Since my last column I've been trying to further my understanding of the physics of this part of the process and undertake a mathematical analysis. This is a "jungle" I wish I had never walked into. I feel like a character in an old Tarzan movie who is caught in quicksand and desperately reaching for a vine to pull myself out.

The problem is that the deeper I dig the more confusing and complicated the problem becomes. Most of the work that has been done on the flow of particulates between rolls analyzes a situation where the goal is to create a very highly compressed sheet of material, such as is sought when working with powdered metals or pharmaceutical powders. This is clearly not the case when working with cereal bars, for which excessive compaction results in a very undesirable texture. In addition, the literature does not agree on how to model such a system. There are different approaches to the compaction of powders, the uniformity of the stress within a slice of product between the rolls, and whether there is partial or complete slip of the product between the rolls. In addition, none of the analyses in the literature consider a particulate that exhibits adhesion to the roll surface, which is likely with cereal bars because of the presence of sticky binders. Nonetheless, one can get some general ideas about what is going on independent of the specific approach taken.

In general, the shape of the pressure exerted on the product, and the related shear on the surface of the product, follows a trend similar to that shown in Figure 1. The pressure and shear increases to some maximum and then declines until the material exits the rolls. At the feed end of the rolls, where the pressure is increasing, the material moves slower than the surface of the rolls as a result of slip. At the discharge end, the slab moves faster than the surface of the rolls, also as a result of slip.

Note, the initial feed pressure to the rolls is not zero. As stated in my previous column, this pressure comes from the "head" above the first point of contact, which results from the collection of material in the hopper. This head is necessary because, unlike a viscous fluid, local pressure results in the creation of a drag force that "drags" the material into and through the rolls. This raises the first question: how does the load in the hopper create pressure on the rolls?

Unlike a fluid material, the pressure created is not arbitrary. For a fluid, the pressure on the rolls increases linearly with the height of the material in the hopper. For particulate materials, the pressure exerted on the rolls increases in an exponential fashion until some maximum is reached. A discussion of this may be found in Tadmor and Gogos (1). Increasing the amount of material in the hopper beyond some point results in virtually no increase in pressure on the rolls and no improvement in the conveying efficiency of the rolls. I'm sure some readers have observed this.

The pressure created by a head of material in the hopper is illustrated in Figure 2. Note that as adhesion to the walls ("stickiness") increases the maximum pressure that can be created is reduced. It is possible to show that if adhesion to the walls is high enough, no pressure develops in the hopper and no flow into the rolls can occur. What does this mean? It's been my experience that some sugar-based syrups are stickier than others. A pure sucrose syrup has a different stickiness than a syrup containing monosaccharides. To improve the performance of the rolls, should we consider reformulating the binder?

This raises a second question: what dimensions should be used for the hopper? As the walls of the hopper get closer together, either front to back or side to side, resistance to flow down the hopper increases. The maximum pressure that can develop at the base of the hopper increases as the ratio of the cross-sectional area to the circumference of the hopper increases. How does this impact the process? As the rolls get wider, the hopper naturally gets wider. For hoppers with the same front-to-back

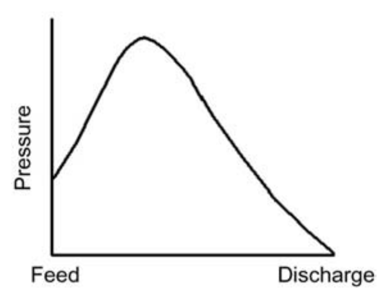

Fig. 1. Pressure profile between rolls.

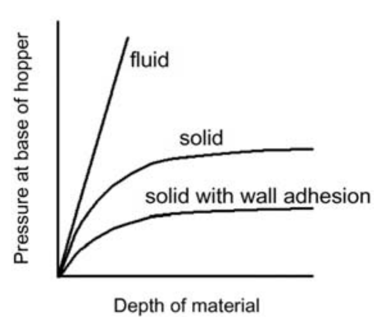

Fig. 2. Pressure at base of hopper.

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dimensions, the maximum pressure that can be exerted on the rolls increases with roll (line) width. This means rolling efficiency, as well as roll speeds required and pressure developed, will change with line width. Therefore, a narrow line will not directly predict the performance of a wide line unless both lines are so wide that the friction of the walls of the hopper can be ignored. Note what this indicates about the predictive performance of a narrow pilot-plant system.

What about the front-to-back (depth) dimensions of the hopper? To maximize the pressure created by the head of material in the hopper, it would seem that the depth of the hopper should be as large a possible to maximize the ratio of cross-sectional area to circumference. This suggests that the wall of the hopper should be positioned at 90° to the rolls (Fig. 3).

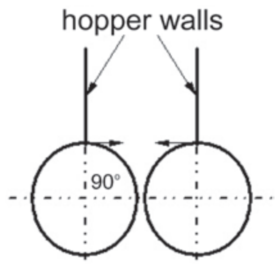

Fig. 3. Hopper positioned at 90°.

It turns out that this may be the optimal configuration for developing initial pressure on the rolls, which is very desirable for efficient conveying. However, there is another issue to consider. The conveying efficiency of the rolls themselves depends on the location of the angle at which the material first contacts the rolls. The arrows in Figure 3 illustrate the direction of the drag flow from the rolls. It is horizontal, which is 90° from the direction in which we wish to convey the material (vertical). There is a point of contact at which the angle maximizes the conveying efficiency of the rolls. The value of this angle depends on the properties of the particulate to be processed. For reasonable estimates of physical properties, the optimal position of the feed hopper is ≈60° in relation to the feed rolls (Fig. 4). Those who have one of these lines determine the angle location on the hopper walls. I would not be surprised if you find the angle is close to 60°—a value that has probably been empirically established by the designers of the system.

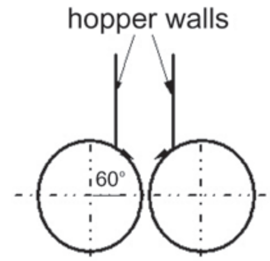

Fig. 4. Hopper positioned at 60°.

One last comment about hopper dimensions. If you have a pilot plant with smaller rolls, they have a different conveying efficiency. This will be discussed in future columns. In addition to smaller rolls and a narrower hopper than is used on commercial lines, the depth of the hopper will also be smaller, further differentiating the conveying efficiency of the pilot line from that of commercial lines.

For my regular and long-time readers, this column marks the approximate anniversary of my first *CFW* column. It's been 25 years since I began these columns! I'm sure this is a *CFW* record by a large margin. Someone owes me a cake!

Reference

1. Tadmor, Z., and Gogos, C. G. Pages 253-255 in: *Principles of Polymer Processing*. John Wiley & Sons, New York, 1979.