CHUTE DESIGNS AND TRAJECTORIES USING THE DISCRETE ELEMENT METHOD

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SYNOPSIS

This paper will investigate the operational behavior of several transfer chutes designed using the discrete element method (DEM). A comparison of impact and wear locations, as well as material flowability, is made between operating chutes and the DEM simulations. Classical trajectory equations are discussed as well as a range of different transfer chute design concepts.

1. INTRODUCTION

Over the years there have been a plethora of papers written on the topic of bulk material discharge trajectories from conveyor belts. It is interesting to note that most papers and experimental measurements generally agree that Booth's[1] equations (1934) seem, to result in the most reasonable flow predictions over a wide range of conditions. Since Booths paper, there have been many subsequent papers comparing various methods to one another. These papers have not only looked at free flowing discharge trajectories, but have derived some very interesting (and in many cases fairly complex) equations written to describe the material flow behavior after it has impacted a control surface. These surfaces include impact walls, rock boxes, curved hoods and curved chutes. In practice, however, utilizing such equations beyond simple material trajectories seems to be more of an academic exercise then a practical chute design tool.

In all fairness, this paper also began as another attempt to provide a modified set of material flow equations which could be applied beyond simple trajectory theory. In the end however, it is the author's humble opinion that these equations don't exist in the real world. The underlying problem to such simplistic approaches is that we live in a 3-dimensional world. The complex and often chaotic behavior of material flow thus requires more advanced solutions.

To further complicate matters, it is often extremely difficult, if not impossible, to obtain accurate and reliable data on most transfer chutes. Be it an existing system or a new installation, the interior world of a transfer chute is simply too hostile an environment to support effective data acquisition. Even opening an access door for photography of the chute flow can be a difficult task. Dust generation, safety concerns regarding airborne material and the limited number of favorable access locations, complicate the task. The installation of video cameras and/or other sensors is also very challenging.

Furthermore, the designers never seem to get feedback on the chutes that operate well, but are certainly informed about those that don't! Visual inspection of wear liners is often the best source of information. Unfortunately, maintenance records with locations and frequency of liner replacement are usually not available. These factors all hinder the engineer's ability to evolve and improve upon successful chute concepts.

The author has great respect for chute designers of the past. Their experience, combined with the ability to imagine how the material would flow under various conditions, has resulted in many ingenious transfer chute designs. There are likely thousands of transfer chutes in operation today. Unfortunately, these crude design practices have also resulted in some chutes which have left the client wondering "what in the world were they thinking!" Furthermore, how many chutes have needed to be modified or completely redesigned?

2. DISCRETE ELEMENT METHOD

The Discrete Element Method (DEM) is the name given to the process whereby the large-scale behavior of a complex material system can be modeled and simulated on a computer. This involves the mathematical modeling of millions of individual discrete “particles” or “clusters of particles”. Figure 1 shows some examples of the DEM method in practice.

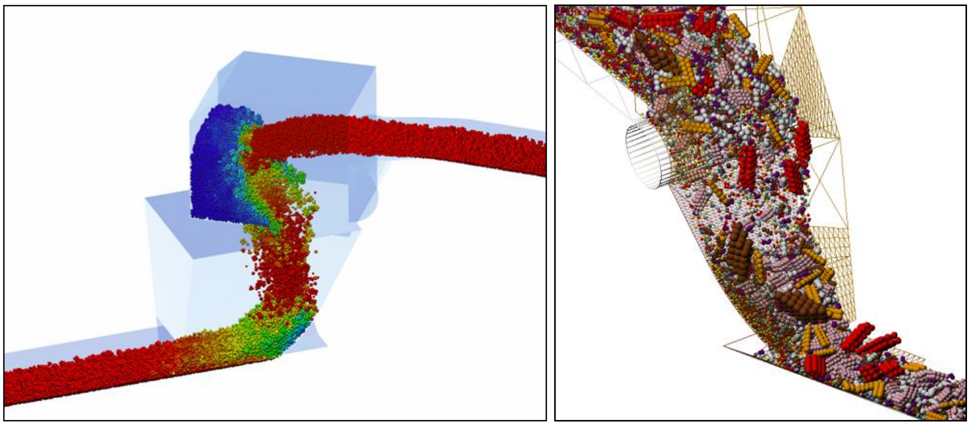

Figure 1: Examples of DEM material flowing through two transfer chutes

For more than a decade, DEM has been used to solve a range of material handling problems. The author has previously published several papers on the theory and technology behind the DEM method[2,3,4] as have others[5,6,7]. This paper, however, is focused on the application of this technology.

The proper modeling of granular flow using the DEM method is one of the most significant scientific advances in the mining industry today. Prior to the DEM method, the only tools available to the designer were general rules-of-thumb and past experience. Now, complex material flow problems can not only be accurately modeled, but various design options can be quantitatively compared against one another. This allows the design to be optimized in a manner never before possible. Additionally, a wide range of “worst case” material properties can be simulated, thereby allowing the designer greater foresight into how the system will behave once it’s constructed.

This process is a radical change from the trial and error methods used in the past. The DEM method should however, be applied and used no differently than any of the other "tools" in an engineer’s toolbox (Figure 2). To be effective, it must be combined with good engineering knowledge, design experience, and a firm understanding of the characteristics of the material being conveyed.

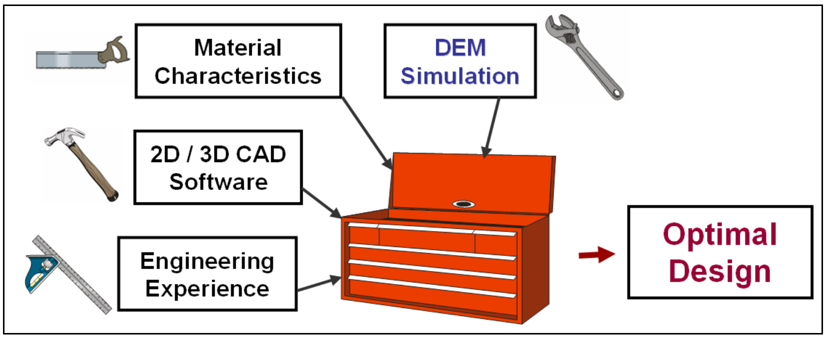

Figure 2: Tools for the optimal design of materials handling equipment

3. MATERIAL FLOW TRAJECTORIES

3.1 HIGH SPEED FLOW TRAJECTORIES

For medium to high speed material flows, the discharge trajectory of a conveyor can be plotted using basic physics and projectile motion equations.

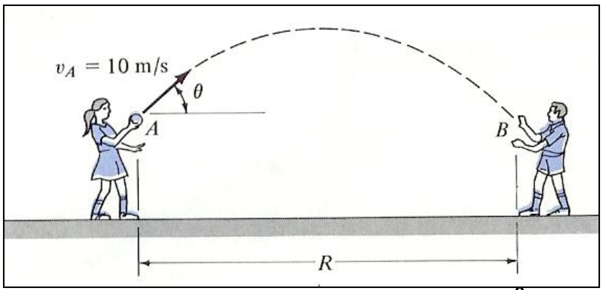

Figure 3: Simple projectile motion [8]

As simple as this seems, it has been fraught with confusion when applied to bulk solids and transfer chutes. The major issues include:

1. What discharge velocity should be used?
2. Are the exit velocities of the top and bottom of the discharge flow equal?
3. How is material “slip” over the head pulley accounted for?
4. Does the flow stream diverge or stick together?
5. How do the cohesive properties of the material affect the flow?

Highly cohesive materials can have a layer of material that “sticks” to the belt’s surface. The main body of material will separate from this layer and continue at its original velocity (Figure 4). Depending on the amount of internal material cohesion and the cohesion between the belt and the material, the velocity vector of the material flow can be altered significantly.

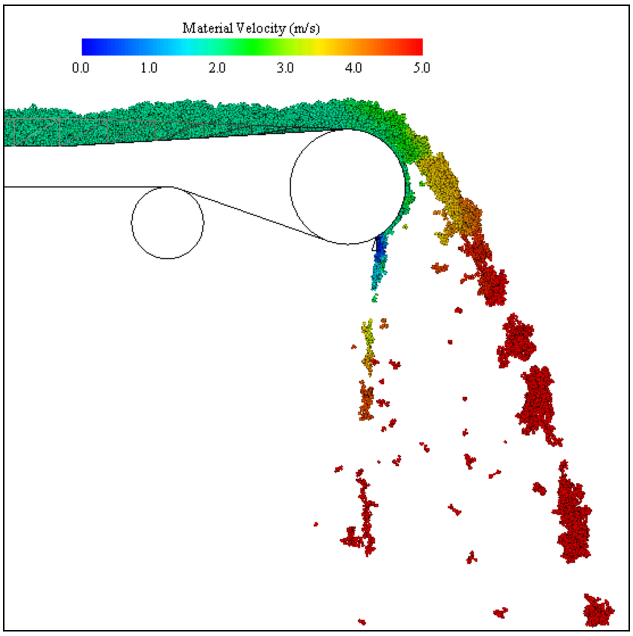

Figure 4: DEM showing layer of high cohesion of material sticking to belt

Figure 5 shows the wear on a typical impact wall for a ROM coal transfer chute. The incoming belt is declined at 6.8 degrees with a belt speed of 4.0 m/s. A dotted line has been drawn around the impact area. Figure 6 shows a DEM simulation of the same chute and material parameters.

Figure 5: ROM coal impact wall

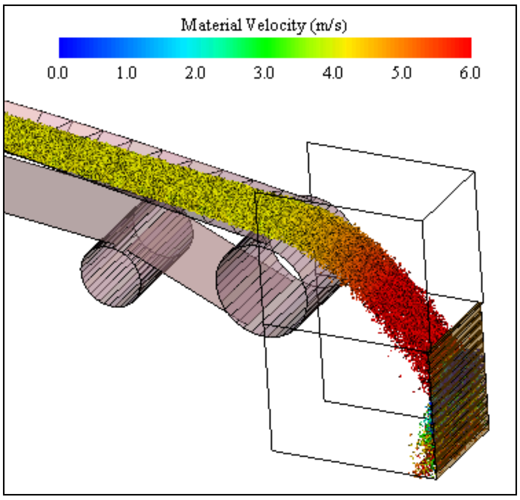

Figure 6: DEM simulation

Figure 7 shows a side view of the flow taken from AC-Tek's Sidewinder conveyor design software. The trajectory profile uses a modified projectile motion theory. The trajectory is plotted using a single line starting at the midpoint of the material stream and using the belt speed as the initial velocity.

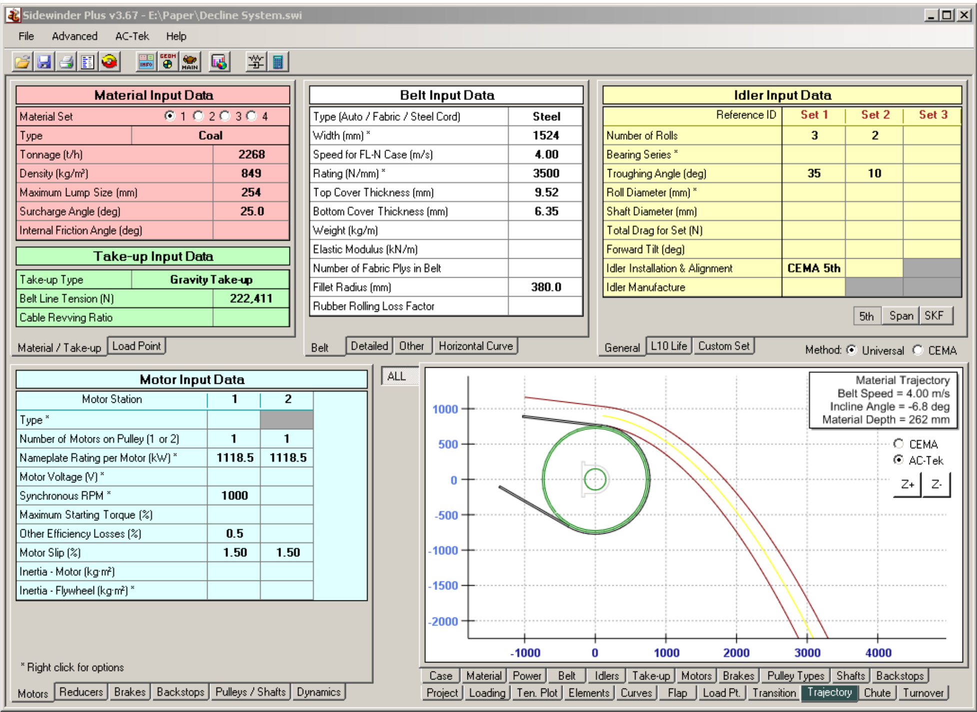

Figure 7: Trajectory calculation using Sidewinder software

Figure 8 overlays the projectile motion equation, DEM modeling, and the measured impact area. Both the DEM model and projectile equations are adequate to predict the impact location.

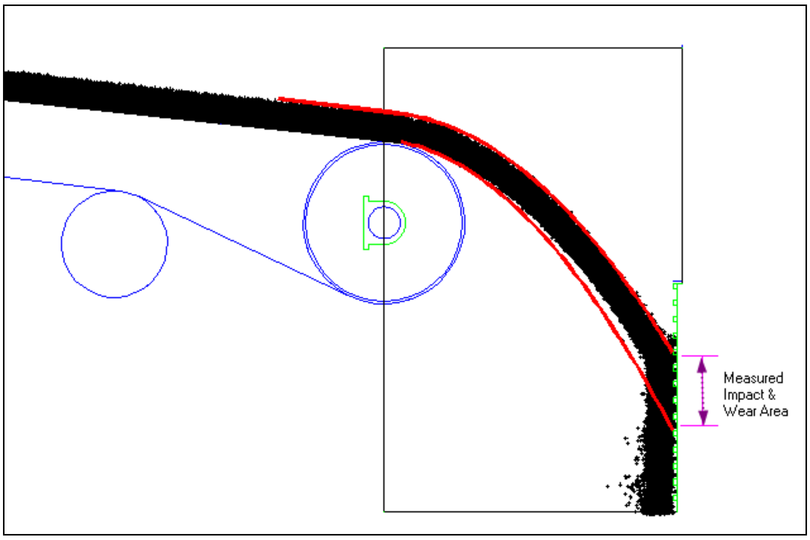

Figure 8: Overlaid material trajectories and measured impact area

3.2 SLOW SPEED FLOW TRAJECTORIES

Figure 9 shows the material flow from the head pulley of a belt feeder. The material speed is 0.1 m/s with a material bed depth of approximately 700 mm. In this particular installation there are three belt feeders which reclaim material under a large conical stockpile. The first and last feeders are positioned towards the outside of the stockpile, whereas the middle feeder is directly under the center of the pile. The stockpile is fed by a single, non-movable conveyor. Segregation effects are easily observed since the coarse material flows to the outside of the pile while the finer material stays in the center. Even with all three feeders operating at the same speed, the resulting material trajectory is quite different due to the percentage of fines in the material flow. Figure 9 shows the central portion of the material flow being almost stationary, while the edges of the flow have begun to slip and accelerate over the head pulley.

This stick/slip flow is readily known and quite prominent when observing these types of flows in the field, but is not included in even the most complex closed form equations for material flow. However, it is quite easy to model this slip/stick behavior using DEM. It naturally occurs when cohesive material properties have been included in the model. Figure 10 shows a time lapse for the belt feeder. Rather than a continuous flow, the stick/slip behavior is obtained. Figure 10 shows the cluster positions at various time intervals, while Figure 11 shows the velocity and position history using vector traces.

Figure 9: Slow speed flow over belt feeder

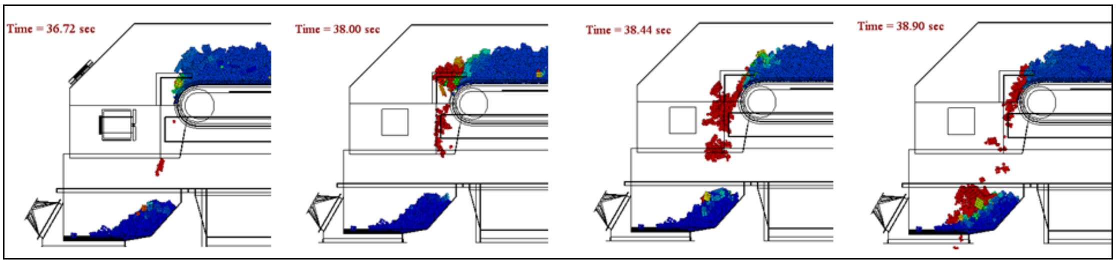

Figure 10: DEM simulation showing the slip/stick behavior of the material

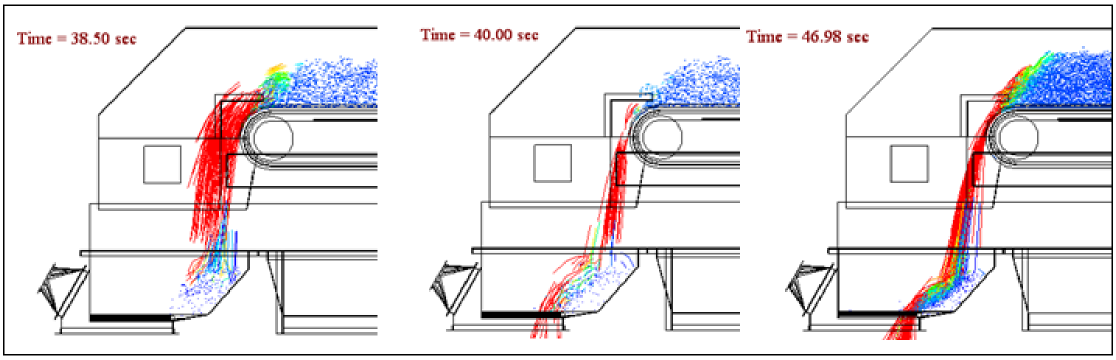

Figure 11: Velocity trajectories – Note the changes in the flow with time.

3.3 IMPACT SURFACE MODELLING

As mentioned previously, various papers have tried to derive a wide range of equations to predict what happens to the material when it encounters an impact surface. These equations range from the simplistic, to the dreadfully complex. Figure 12 shows several problems when trying to apply classical equations to even the simplest transfer chutes.

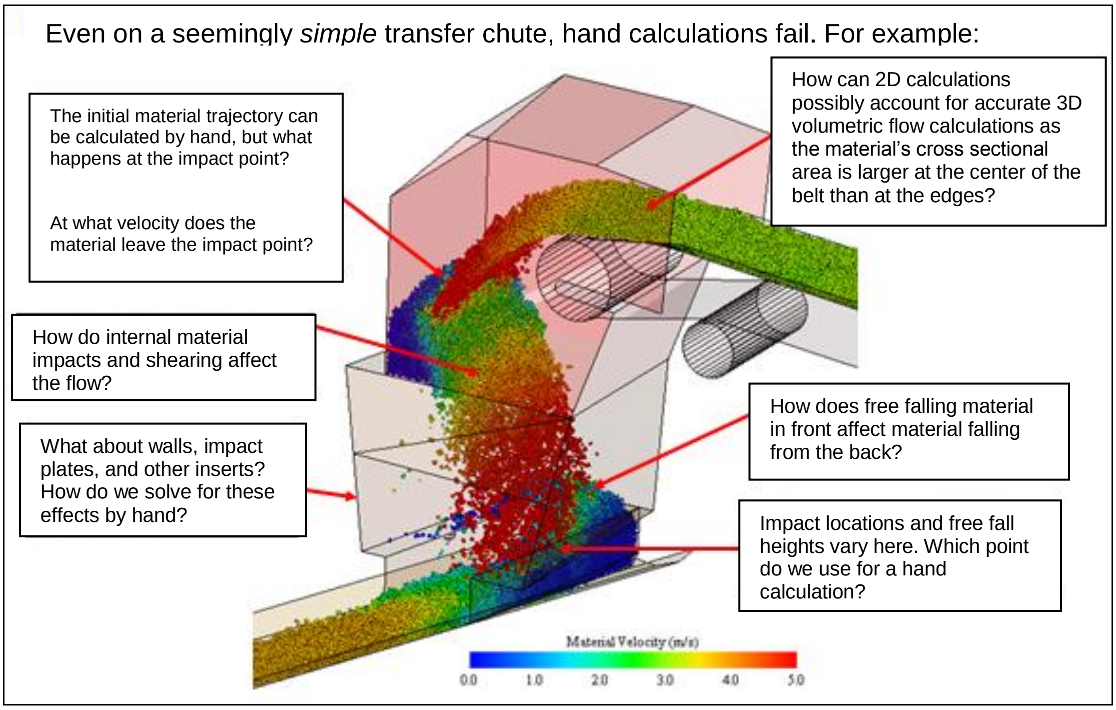

Figure 12: Fundamental problems with simple projectile motion equations

One of the most basic problems with classical 2D equations and approaches is the concept of mass conservation. When the material flow impacts a wall, it will diverge in all three dimensions. But the very purpose of many hood and spoon designs is to converge the material flow. The fundamental concept of mass conservation is lost with simple projectile motion equations. The behavior of the material inside of the flow will differ significantly from the material behavior along the outside edges. Furthermore, most transfer chutes have relatively complex geometries, none of which are convenient for hand calculations.

Here again, DEM proves itself to be an extremely powerful tool. By its very nature, DEM can handle virtually any 3D geometry that can be drawn in a solid modeling program (AutoCAD, Inventor, Solid Works, etc). Mass, momentum and energy are all conserved as required by the fundamental laws of physics.

4. VARIOUS TYPES OF TRANSFER CHUTES

This paper will touch on several types of transfer chutes. Certainly there are many others, but these seem to be the most common. They Include:

1. The "Ideal Chute"
2. Inline Transfer Chutes
3. Rockbox Transfer Chutes
4. Flow Containment methods (hoods, curved chutes, etc)
5. Combined Rockbox and Chute Arrangements
6. Adjustable Chutes

None of these chutes are new or revolutionary. They have all been around in some way, shape, or form for quite some time. There is no such thing as "one size fits all" in transfer chute design. Different chutes have different advantages and disadvantages.

4.1 THE CHICKEN OR THE EGG

Before discussing transfer chute design, it’s worth noting that transfer points have historically received a bit of a “bad rap” through no fault of their own. They are a vital piece of any material transporting system, yet are often designed as an afterthought. More often than not, the conveyors have been designed, discharge height specified, head pulley positions set, and structural drawings complete, all before the poor transfer chute gets any significant engineering attention. In many systems, it is painfully obvious that chute design came as an afterthought. A poorly designed chute results in countless late nights, unscheduled downtime, excessive maintenance and missed production quotas.

Why not design the transfer chute first? Transfer heights, head pulley positioning, and other factors should always be dictated by the chute design, and not the other way around. In many instances, even belt speeds may need to be dictated by chute requirements (which may seem like a completely foreign concept to many). As with the chicken and egg analogy, so should be the conveyor and chute design. Both are essential to each other; both require equal thought from the beginning. And neither one can come before the other.

4.2 THE “IDEAL TRANSFER POINT”

Figure 13 shows the author’s idea of the world’s simplest, time tested, scientifically proven, and completely wear-free chute. Yes, the image is supposed to be blank. That is because the ideal chute is one that simply doesn’t exist. With current conveyor technology and the advances in horizontal curve design, multiple transfer points can (and should be) eliminated. In many cases the operating risks (potential belt damage, accelerated belt and liner wear, and increased maintenance costs) associated with even one additional transfer point can easily exceed those of a horizontally curved conveyor.

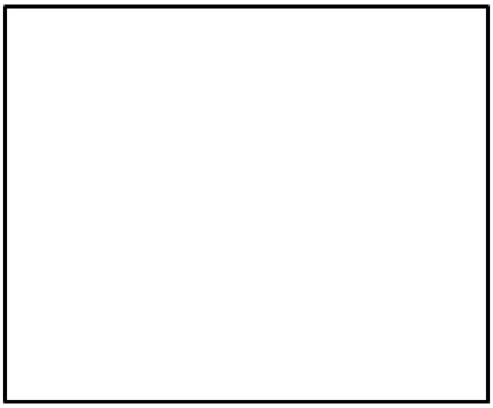

Figure 13: The Ideal Chute - None at all

These technologies are not new, and horizontally curved conveyors have proved effective worldwide. Designs which were considered impossible only a few decades ago are now commonplace.

4.3 INLINE TRANSFER CHUTES

Opposite the “ideal” transfer chute are the “Frankenstein” transfer chutes. The author is often completely perplexed by some of the monstrosity chute creations for some seemingly simple transfer points. The “kiss” acronym (keep it simple stupid) is only too applicable to most chute designs. Not every transfer point can be eliminated, but more often than not, the simpler the chute design, the better.

Figure 14 shows a design concept of an inline transfer point for low cohesion materials. With this design the material is gently guided from one conveyor to another with minimal drop height between the conveyors. The angle of the chute (with respect to horizon) is a function of the belt speed, and the material’s cohesive properties. Both impact and abrasion wear are minimized. Furthermore, due to the smooth material transition, particle impact and dust are significantly reduced.

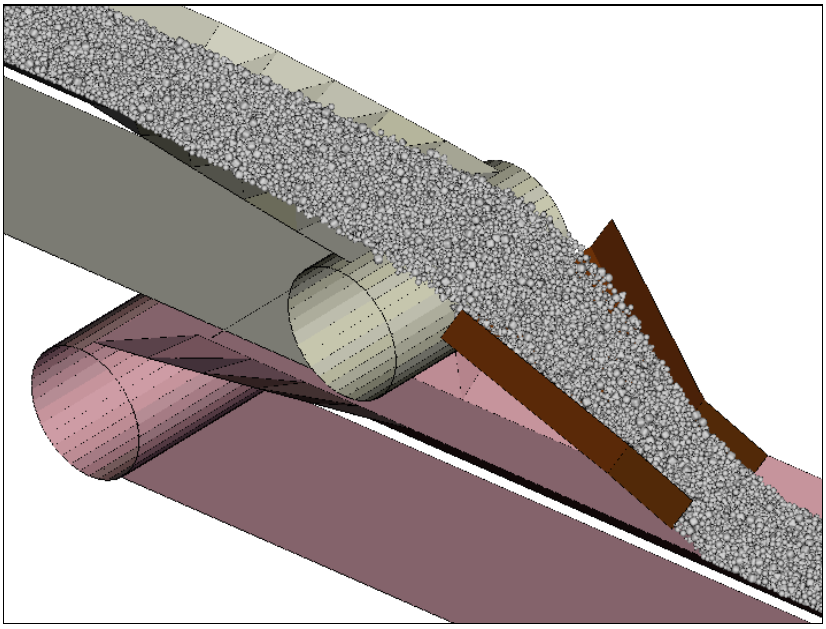

Figure 14: Inline Transfer Chute – Isometric View

4.4 ROCKBOX TRANSFER SYSTEMS

Rockbox transfer chutes have been used for years. The basic concept is to allow the material to impact upon itself in order to change its velocity and direction. This eliminates, or at least greatly reduces liner wear and maintenance. Figure 15 shows a rockbox system transferring 2600 t/h of highly cohesive iron ore.

The chute was designed using DEM technology (Figure 16) and commissioned in mid 2008. In total, five similar chutes were installed at the mine. Each chute was optimized using DEM. All chutes are operating successfully and have minimal wear with excellent material flowabilty.

Figure 15: Inline Transfer Chute – Isometric View

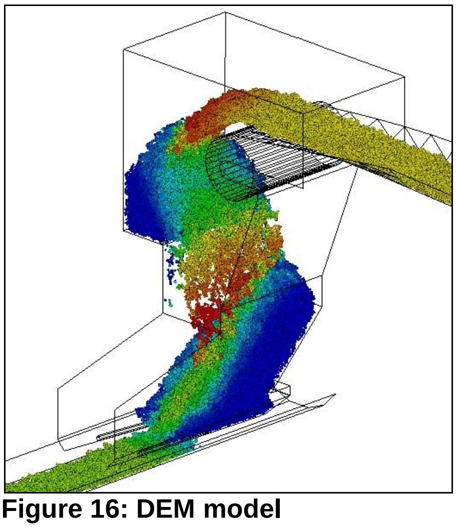

Figure 16: DEM model

Figure 17 shows a triple rockbox arrangement for rotating the material flow 180 degrees. This particular chute was required for a milling reclaim circuit inside a building. Minimizing the transfer point height and eliminating any direct impact (wear) surfaces was a crucial design parameter.

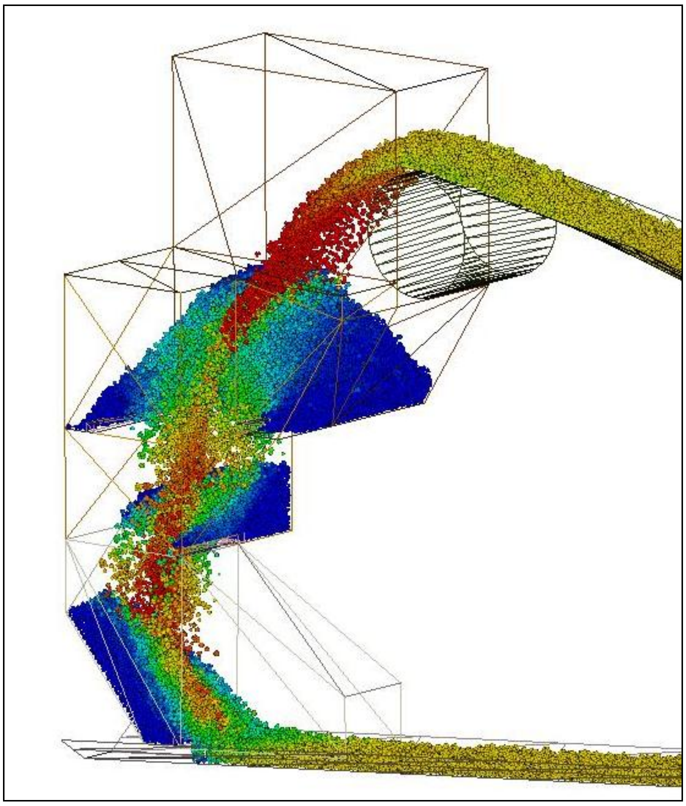

Figure 17: Three-stage rockbox

Figure 18 shows a simple, yet very effective implementation for an adjustable rockbox. Long, thin plates (or railroad ties, I-beams, or solid square bar), are used to make up the floor of the rockbox. The bars extend out through the front of the rockbox. They can be supported externally, internally, or a combination thereof. By using individual sections and allowing these sections to be movable in the field, a highly adjustable rockbox can be created. The entire ledge of the rockbox can be moved in or out to create a deeper or shallower rockbox as needed. On transfer points with oblique angles (i.e. the receiving belt is 10-80 degrees from the feeding belt) these bars can be moved to meet the required angle. This adjustability can make the difference between a chute that's completely unacceptable, to one that flows smoothly while evenly centering the flow on the receiving belt.

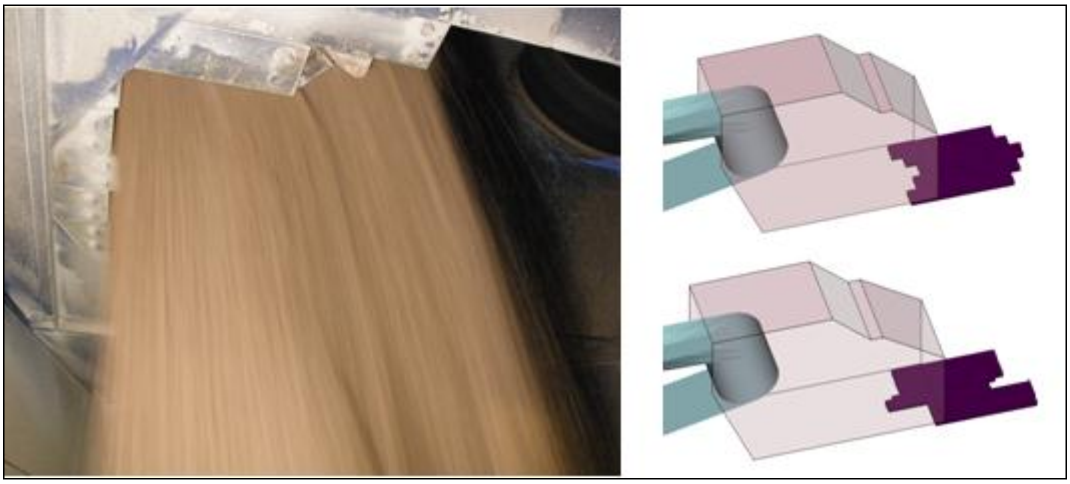

Figure 18: Adjustable rockbox design using individual wear plates for the rockbox floor

Another advantage of the DEM method is the wide range of material properties that can be simulated. In many cases the exact material properties may not be known. In these circumstances, "worst case" flow conditions are used. This typically results in the simulation of both "free flowing" and "highly cohesive" material conditions (Figure 19). The free flowing condition will typically highlight areas of high wear and show if the material load centering is of any concern. The high cohesion case can be used to predict chute build-up and plugging.

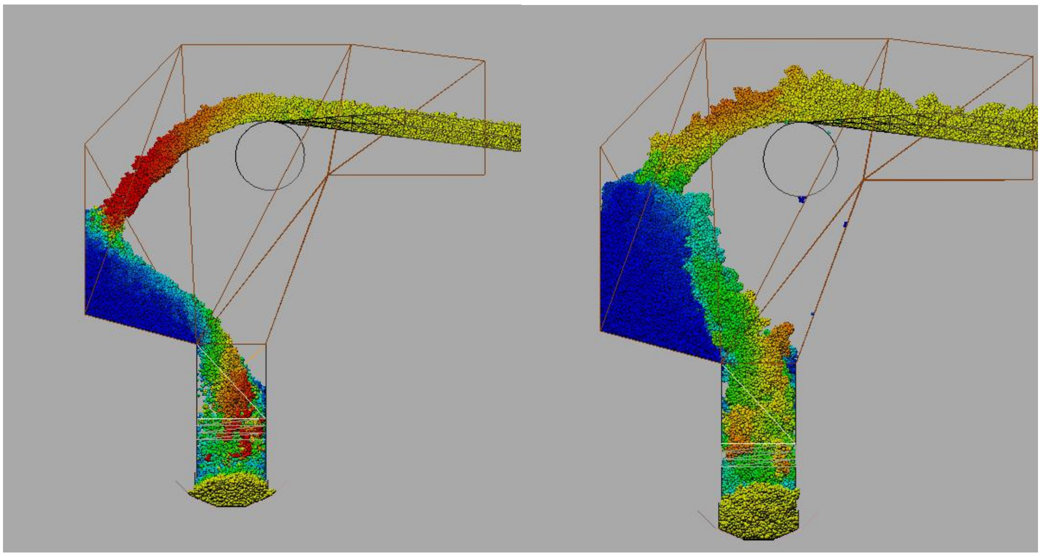

Figure 19: Free flowing and high cohesion material flow through a right angle rockbox

One disadvantage of a rockbox type arrangement is that it generally requires more physical size due to the rockbox capacity. Additionally, rockbox designs can result in more turbulence and material impact. For some material this can result in more dust generation and material degradation than other transfer chute designs.

4.5 FLOW CONTAINMENT METHODS (HOODS, CURVED CHUTES)

Curved chutes can be separated into an upper curve chute (hood), and a lower curved chute (spoon). Some designs might incorporate a single hood or a spoon, whereas others may incorporate both.

A typical hood arrangement is shown in Figure 20. For many applications and materials these types of chutes are excellent. However, they should be designed to “capture and guide” the material flow, not to provide an impact surface. This is yet another reason why it is so important to get the basic material trajectory correct. Regrettably, many times the line between “guiding the flow” and “impacting the flow” becomes blurred. The hood ends up too close, or at too high an impact angle to the material flow. In this case, the hood liners can wear through in a relatively short time period (Figure 21).

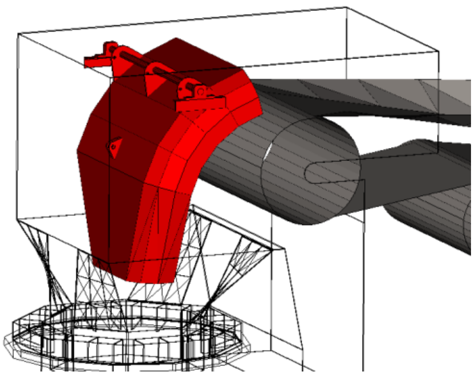

Figure 20: Hood Chute

Figure 21: Wear on a hood chute

If a hood is to be used as a high impact area, then a hybrid hood/rockbox arrangement can be implemented. Figure 22 shows an impact hood arrangement with individual rockbox ledges to reduce liner wear.

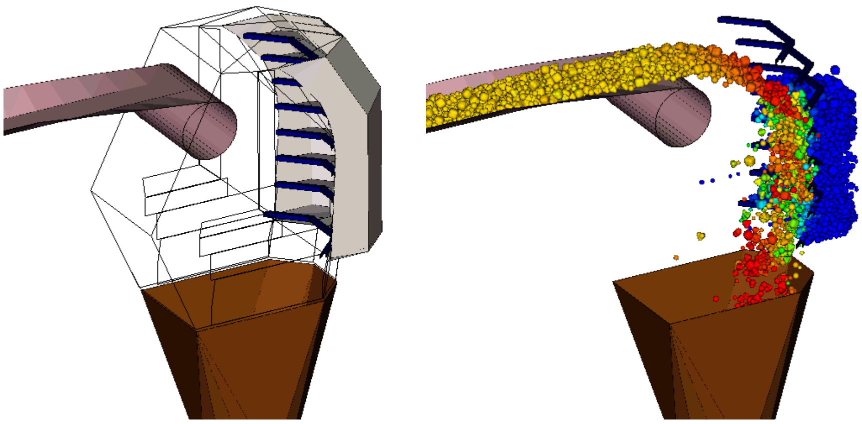

Figure 22: Hood with rockbox ledges

4.6 COMBINED ROCKBOX CHUTE ARRANGEMENTS

In many situations the combination of an upper rockbox and lower curved chute can be an excellent option. The upper rockbox is used to stop the material flow and rotate its direction. The lower curved chute maintains the material speed while gently guiding the material onto the receiving belt. The goal is to match the material's exit velocity with the belt speed, and minimise the impact angle. But the chute wall angles must be kept steep enough to avoid material build up and a plugged chute condition.

By its very nature, the DEM method calculates the forces on every particle throughout the simulation. This also includes any surfaces with which the material comes in contact (liners, belt, etc.). Different surfaces may therefore be given different frictional properties. Furthermore, the impact and abrasion wear on any surface can be recorded over time (Figures 23 and 24). This not only allows the simulations to highlight high wear areas, but even more importantly, allows different designs to be compared to one another. This is a major step forward in the optimisation of transfer systems.

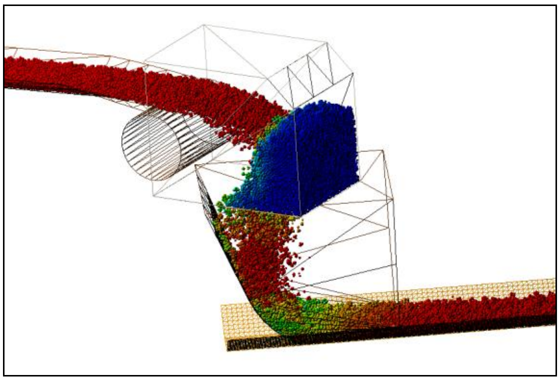

Figure 23: Rockbox with curved chute

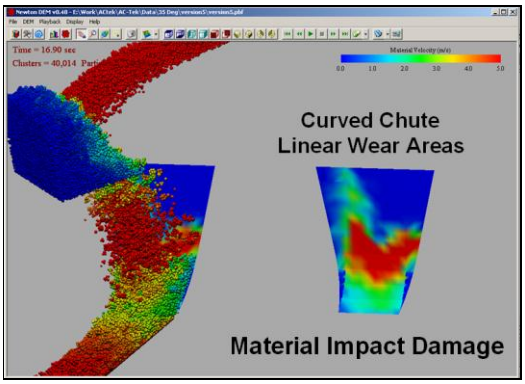

Figure 24: Impact and wear areas from DEM

Depending on the specific chute design, the lower curved chute can still experience a high amount of impact wear from the upper rockbox. An even better design can be constructed by using both an upper and lower rockbox, with a small curved chute at the exit (Figure 25). This design eliminates all major impact wear while still utilizing the curved chute to rotate the flow and guide it onto the receiving belt. Combining the upper rockbox with an adjustable surface (as described earlier) results in a design that works well for a wide range of materials and transfer angles. A disadvantage of these types of chutes is that they often require more vertical height then other designs. However, many overland conveyors feed onto much shorter stacking conveyors. On these systems the increased height (and thus storage volume) may be required for material build in a power failure condition.

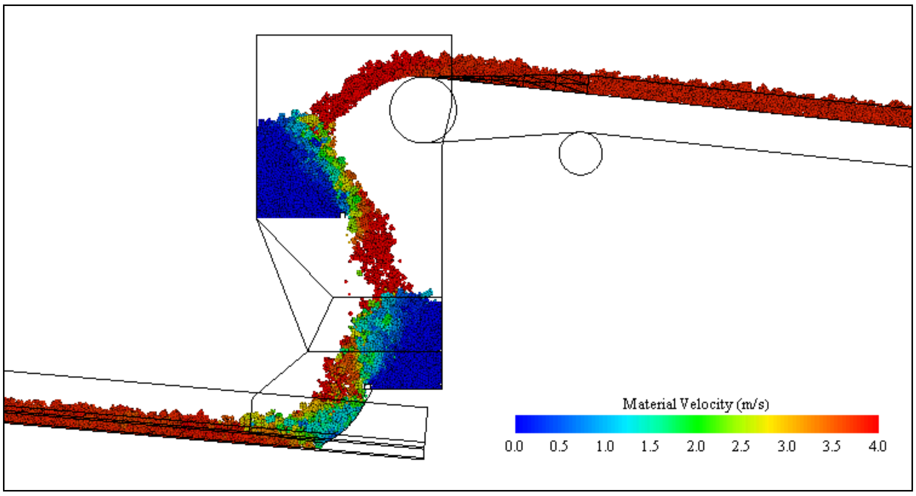

Figure 25: Upper and lower rockbox with curved chute

5. CONCLUSION

This paper has discussed various aspects of transfer chute designs. Although simple projectile type equations can be used for very basic chute layouts, better solutions are available. Projectile equations do not take into account even the most basic material properties and cannot predict material flow beyond the initial discharge trajectory. DEM technology is no longer a “new” technology. It has evolved into an extremely powerful tool for the designer, and its application has been proven in the field. Even so, proper use and implementation of DEM still requires a relatively high level of experience, and not all DEM programmes are created equal. Various types of transfer chutes have been discussed along with their strengths and weaknesses. In the end, there is no such thing as “one size fits all” when it comes to properly engineering a transfer system.

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