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A numerical investigation assessing the symmetry of burden charging in a blast furnace using different chute designs.

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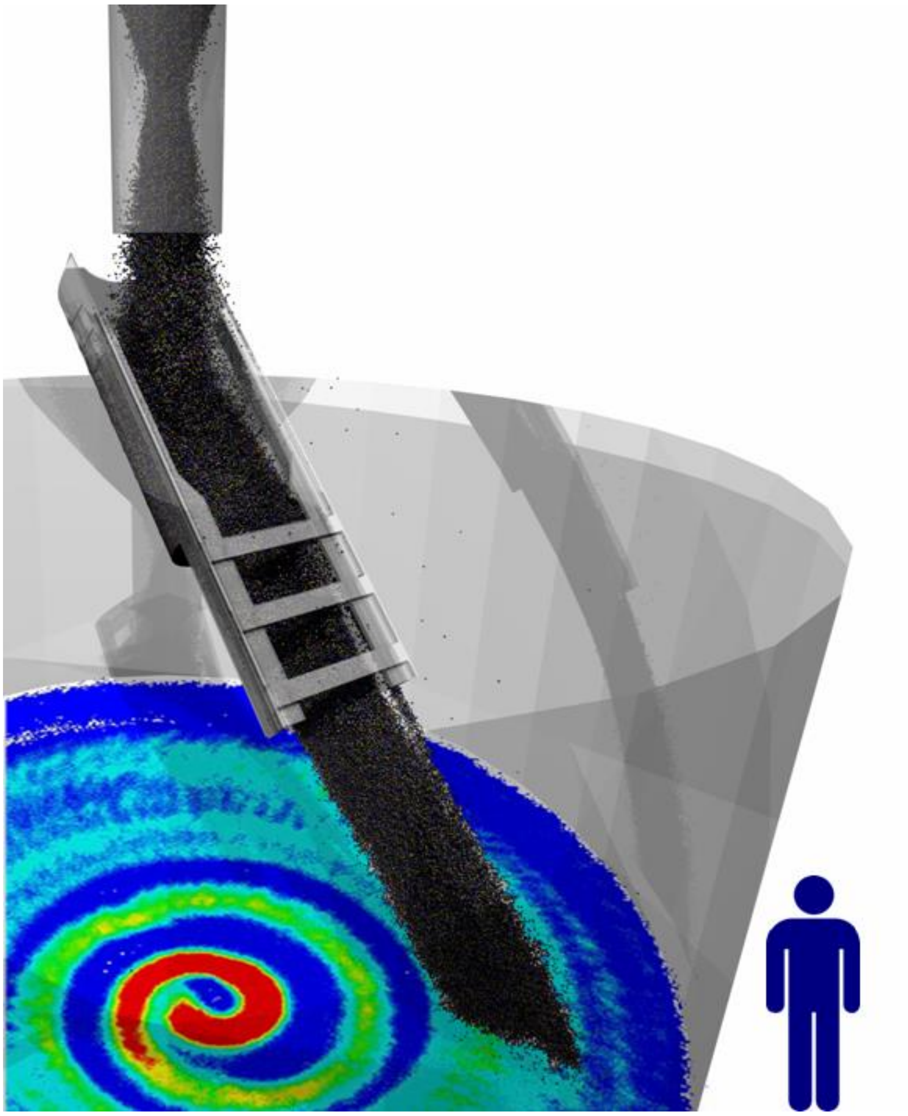
Abstract

A full-scale 3D numerical model using the Discrete Element Method is used to investigate three different chute designs for the charging of a blast furnace. The three chutes differ in the proportion of the chute that is either smooth or contains rock boxes. The uniformity of the delivery of burden materials is assessed as burden passes through a 2D plane is used to determine the relative merits of the three designs. The chute composed entirely of rock boxes was predicted to provide the most homogeneous delivery of material to the top of the blast furnace according to the criterion above. Choice of chute design is discussed with reference to the historical movement away from the older ledge-charging strategies to the more modern chimney-charging strategy.

Graphical abstract



Schematic diagram showing predicted burden delivery distribution form a full scale 3D DEM model for a blast furnace.

Highlights

A full-scale 3D DEM model is used to predict burden delivery distributions in a blast furnace providing a methodology with which to compare different chute designs.

Keywords: Discrete Element Method, Blast Furnace, Chute Design, Burden Distribution.

1. Introduction

Ideally the proper operation of a blast furnace should provide high productivity over a long campaign life in a sustained and reliable manner. There are various strategies that iron makers will adopt to achieve this ideal and the manner in which raw materials (burden) are charged into the top of the furnace is the first critical step. Different layers of coke, sinter and iron ore pellets are introduced into the top of the furnace in a systematic way to achieve a desired layered structure of granular material in the furnace. Blast furnaces reduce iron ore into iron through reduction with coke and the burden distribution should be axisymmetric about the vertical axis. Symmetry is important because computer models and plant operating procedures currently employed at Tata Steel are all based on the assumption of a symmetrical structure within the furnace.[1] Figure 1 shows two possible layer patterns, the older ‘ledge’ pattern and the more modern ‘chimney’ pattern. Ledge charging was the preferred charging style of the past. Material is charged near the wall and settles to create layers of coke and iron all the way across the furnace. The “chimney” approach provides the conditions (permeability distribution) for a high central cohesive zone, one problem that can occur in this region is where materials begin to “join” together and form internal bridges within the furnace.[1] This bridging behaviour can prevent descent of material in the blast furnace. [2] Managing the cohesive zone shape is one of the most important tasks in blast furnace operation. The shape is controlled by burden distribution (coke/ore distribution and burden material size distribution). The burden distribution and shape of the cohesive zone are highly coupled with the gas flow in the blast furnace. Optimising this flow is important to achieve maximum chemical and thermal efficiency and reduce damage to furnace refractory linings.[2] The shape of the cohesive zone has a major influence on burden movement. Poor burden descent is often associated with problems in the cohesive zone. No burden descent at all (hanging) or sudden uncontrolled burden descent (slipping) are largely consequences of the cohesive zone configuration acting in combination with other factors. Correct charging of burden at the top of the furnace is essential to the stability and correct shape of the cohesive zone.

1.1 Chute designs

The blast furnace under consideration in this work uses a Paul Wurth Bell Less Top charging system. As confirmed by plant monitoring equipment, burden falls at a steady rate from a hopper onto a rotating chute.[1,3] The chute rotates around a fixed vertical axis and both its rotational speed and inclination can vary (figure 2). The chute distributes the burden at the top of the furnace to build up the desired layered structure. There are three chute designs considered in this investigation which are identified as ‘rock box’, ‘straight chute’ and ‘hybrid’. All three systems have been or are being used by Tata Steel.[1]

The ‘rock box’ design contains several open compartments along the entire chute length (figure 3). These compartments quickly fill with burden which provides a shield of sacrificial material that protects the chute from subsequent burden material falling onto and moving along the chute. This design, which in discussions with plant operators is the most resilient to wear, tends to produce a more scattered delivery of burden material to the top of the furnace. From plant data such chutes typically function for several years before replacement is required.

In contrast the ‘straight chute’ has no open compartments. The straight chute is effectively a smooth steel chute with no protection from falling burden (figure 4). This design tends to produce a much more focussed stream of burden to the top of the furnace. However from plant data, straight chutes typically require multiple replacements per year and they are heavily damaged at the end of a campaign, often displaying large holes in the chute[3].

Finally, the ‘hybrid chute’ is made up of approximately two-thirds rock box and one third straight chute (figure 5). This design combines the resilience of the rock box design with the more focussed stream of burden material associated with the straight chute. Again from plant data in contrast to straight chutes, hybrid chutes are typically replaced once per year displaying little damage and providing a consistent charging behaviour over the campaign. [3]

2. Material and methods

A soft-sphere discrete element method (DEM) approach is used to investigate the charging characteristics of three different chute designs. The in-house DEM code used is a full 3D, to scale, simulation. Written in FORTRAN90 the model can simulate 70s of charging with 7.5 million spherical particles in approximately 2 days on an 8-core PC. The DEM force model is shown in figure 6 and Table 1 summarises the model parameters used. The parameters used are based on validation experiments using real burden materials in rotating drums and slump tests (to correctly simulate angles of repose).[1] By matching both the behaviour of dynamic (rolling drum) and a simple static (slump test) the calibrated material parameters chosen here should correctly simulate the behaviour of the burden material during blast furnace charging (figure 7). Although the simple slump test used is operator dependent it still provided reproducible and useful model validation data. For the purposes of comparison it is also assumed that a chimney burden distribution is the target layered configuration. Both the rotation speed and changes in chute inclination have been taken from current operating practice that attempt to create such a distribution. The chute inclination angle is based on the mass of burden remaining in the hopper above the chute. Radial symmetry of burden charging is critical to achieve optimum furnace performance. Therefore, the uniformity and symmetry of burden loading achieved by the different chutes is used as the criterion to assess which chute design is best.

3. Numerical models

There have been several reported modelling investigations of granular material travelling along chutes. Mio *et al* attempted a physical validation of the rolling friction when simulating sinter particles in DEM by using a situation for a non-rotating chute with a hopper above and collection boxes.[4] The behaviour of real particles was recorded and matched by a DEM model. In this work a uniform rolling friction was used which resulted in an over-calming of the flow. The correct flow of sinter particles was not achieved. Then, by using a variable rolling friction (based on particle shape), the model was able to accurately simulate the physical model.[4] Rolling friction, when implemented properly, resulted in a reduction of the spread of particles by absorbing the impact energy rather than allowing particles to bounce unrealistically. Mio *et al* subsequently modelled a sinter charge moving down a basic flat chute onto a coke bed.[5] The coke bed was made up of pre-positioned non-moving coke particles which were generated to match furnace scans. The coke particles from the top surface areas and down to a depth of about 1m from the surface are free to move, while coke particles at greater depths are fixed. A simple hopper and straight chute with a dampener installed on it were modelled over a 5m radius furnace. The chute only rotates through a 90° segment of the entire furnace and does not change angle during loading. An analysis of the flow down the chute found some particles where affected by centrifugal force and exited the chute very quickly whereas others were relatively unaffected by the force and exited the chute slowly. Small particles would get pushed to the wall whereas larger particles accumulated along the centreline of the chute. The entire flow down the hopper was twisted from start to finish and size segregation of particles occurs due to different amounts of acceleration being imparted at different positions on the chute. Finally, Mio *et al* used DEM to simulate charging of sinter and coke with a top hopper.[6] They employed a random distribution of simple rolling friction, but results are inconclusive – there appears to be a separation of material towards the centre of the domain. Wu *et al* simulated a parallel hopper system looking specifically at segregation and design.[7] Shirsath *et al* provided experimental results for monodisperse granular flow through an inclined rotating chute.[8] They showed that the Coriolis Force does not affect the granular flow behaviour via the Rossby number. They also show that the centrifugal force is dominated by gravity preventing material from being held on the chute.

Yu and Saxen have reported DEM simulation results investigating particle segregation[9] and inter-particle percolation of pellets[10]. Mio *et al* report a model of a Bell charging system dealing with asymmetry effects.[11] Also a blast furnace bell-less top simulation looking specifically at hopper charging was undertaken by Yu and Saxen.[12] In this work segregation and clumping of particles were considered and visual experiments were replicated. The study showed that particle shape had little effect on size segregation, and importantly the use of spheres matched the physical results best. In related work, Zhang *et al* simulated a bell-less top charging system albeit it with very large particles (>60mm) on a very simple chute with unrealistic chute angle changes.[13] They employed a Coulomb friction model the numerical limiters of which were a combination of both dampeners and springs operating normally and tangentially.

Kou *et al* used DEM to model the burden distribution in the upper zone of a COREX® furnace (similar to a blast furnace but using oxygen rather than an oxygen/nitrogen mix).[14] The paper described a simulation of coke charging via a gimbal top®. In contrast to a blast furnace, the gimbal chute only rotated at a fixed angle and charged onto a flat layer. Liu *et al* recently reported another DEM model for burden distribution albeit not to scale.[15] They make some conclusions, for example that for a fixed chute angle the burden trajectory leaving the chute is not affected by flow rate. While they use only a simple model for bending friction (a decomposition of rolling rotations into bending and twisting rotations described by Kuhn and Bagi[16]) they employ a more complex dash-pot slider for slip. In this work they begin looking at coke rings over the whole sector, but most emphasis was placed on particle positions while on the chute.

In this paper a DEM model has been used to describe the filling of a blast furnace.[17] The model was developed in collaboration with Tata Steel[1] and implements a variety of friction models that can handle rolling, bending and twisting frictions for general large scale [18] and small scale [19] granular flow problems. A schematic of the force model used is shown in figure 6. [1,18] In this paper the symmetry of charging is assessed by plotting the total mass distribution of burden passing through a 2D plane just above the top level of burden material in the furnace (figure 8). Once particles have passed through this plane they are removed from the simulation. This allows the code to run a full scale simulation in less than three days, which was a practical requirement of Tata Steel. This modelling approach and the results arising therefrom are very similar to 2D trajectory based methods currently used on site.[20] The results obtained using this mode is the subject of this paper. This particular mode has been deliberately formulated to provide a practical tool for blast furnace operators. In other simulation modes the particles are tracked continuously, even after they have passed through the 2D sampling plane and the build up of layers of different burden materials, interlayer mixing, ‘pushing’ effects etc. can be simulated. These latter effects are currently being assessed and will be the subject of subsequent publications. For different burden materials different standard charging sequences have been developed by blast furnace operators. Four such sequences used by Tata are considered; they are defined as coke (D1 & D5) and iron ore pellets (D2 & D4). Also, three historical charging sequences are modelled. These charging strategies in table 5 model the ‘ledge’ type charging strategy of the furnace (figure 1).[20] Details of the percentages of the standard charge introduced at particular chute angles are provided in tables 2 to 5. Charging is always carried out from higher to lower chute angles (i.e. from the wall to the centre of the furnace).

3.1 Modelling assumptions:

1. The sizes of all types of burden material follow uniform distributions between the size limits given in Table 1. Breakage of burden material and material smaller than the lowest size is not accounted for.
2. Air/gas resistance as burden particles fall is negligible i.e. no gas flow.
3. Chutes remain undamaged throughout the charging simulations.
4. Impact of falling burden does not change the chute inclination angle; the angle is determined solely by the mass of burden remaining in the hopper as defined by current furnace operating practice.
5. Each test run assumes the chute is clear of material from the previous run.
6. Based on plant monitoring data the hopper provides a constant stream of burden to the chute.
7. The chute rotates at a constant 8 rotations per minute.
8. The time taken for the chute angle to change from one angle to another is taken directly from Port Talbot plant monitoring data; the change of angle is not immediate it occurs at 1.5 degrees per second.

3.2 Simulations

A series of simulations have been performed and results are analysed in terms of the symmetry of burden delivery. Table 2 lists the simulations. Series 1 and 2 are for coke charging using sequences D1 and D5 respectively (Table 3). Series 3 and 4 are for pellet charging using sequences D2 and D4 (Table 4). Series 5 is for the older ‘ledge charging’ strategy using the hybrid chute design only. As described above the charging strategies for Series 5 are derived from historical data when the ‘ledge’ type charging strategy of the furnace (figure 1) was used (Table 5).[20] This methodology relies much more on the natural slump of all granular materials to build up symmetrical layers rather than trying to deliberately place material at specific locations using chute angle changes.

4. Results

Figures 9 to 12 show the predicted burden delivery distributions for Series 1 to 4 respectively in terms of the mass of burden material delivered. Apart from the normal situation of burden *falling onto* - *moving down* - *exiting* the chute, the DEM model is also able to capture other effects. For example, the movement of burden material that is still on the chute during an angle change or, at low chute angles, burden falling directly into the furnace bypassing the chute completely. For the D1 coke charging patterns in figure 9 it can be seen that the straight chute results in a non-uniform, non-symmetric distribution. The rock box gives the most even distribution, which is largely symmetrical, the hybrid chute falling somewhere in between. The results for the D5 charging patterns are similar and in both cases an incomplete outer ring is noticeable for straight chute simulations. In both cases a more uniform symmetrical result is obtained using the rock box.

For the cases of iron ore pellet charging, the D2 charging sequence shows significant asymmetry for the straight chute design and incomplete outer rings for the straight chute and hybrid chutes. The rock box has achieved the best result in terms of uniformity although poor charging at the outer edge is still evident. For the D4 pellet charging simulations there is significantly non-uniform charging (sector charging) towards the centre of the furnace with several areas receiving a large amount of material as the chute spirals inwards towards the centre of the furnace. In all of these cases, for both coke and pellet charging, the predicted results for the rock box chute design give the most uniform delivery of burden across the furnace. This is most noticeable in the pellet charging simulations.

Figure 13 shows the predicted burden delivery distributions for Series 5 using the hybrid chute design. Using this historical charging technique more material is delivered closer to the furnace wall with the aim of allowing it to slump towards the centre naturally. Angle changes to the chute are confined to a more limited range (Table 5) i.e. the minimum chute angle is 24º rather than 10º. As material is delivered over a relatively smaller area more chute rotations occur before any angle change. This results in more ‘overwriting’ of any given area by burden and leads very symmetrical burden delivery distributions in all three cases.

5. Discussion

The predicted charge patterns from the model are non-symmetrical with complete and partial rings as well as spiral burden loadings being predicted. The changes of chute angle do not occur instantaneously and material that has been built up on the chute may unload in an unsteady manner as the chute angle decreases. The rock box design suffers least from this effect as more material is able to remain on the chute after the first initial pass where the rock boxes fill almost immediately. Even at low chute angles material will remain in the rock boxes, whereas for the smooth chute no material builds up. In this paper the rock boxes are empty at the very beginning of the simulation. This is largely due to higher angles of repose being possible for material on this chute resting on the stored material in the rock box compartments. The rock box chute provides the greatest spreading effect of charge whereas the straight chute provides the least amount of spread, the hybrid chute being somewhere in between the two.

The historical ledge filling strategy is suited to low spread chutes as it relies on the natural slumping of the burden material to control the layer profile. This approach appears to provide more symmetrical delivery of burden (figure 13). Because there are no large angle changes and the charging angle is always relatively high the use of a precise (i.e. low spreading) chute means that there is good control of the central location of the stream of filling material. Subsequently natural slumping of the material, controlled by the angle of repose, would redistribute the material. Also, in this historical approach material charging occurs over more revolutions for any given chute angle. This increased ‘overwriting’ of the same area would also provide more homogeneous charging distributions.

The modern charging strategies rely more on the direct placement of burden material to specific areas by using a greater number of charge positions and chute angles. However, low spread chutes do not appear to perform so well in these cases and the most uniform distributions of burden are predicted to occur using the rock box chute design. In the modern charging strategies, because the chute angle change is not instantaneous, partial ring charging is predicted to occur. This may lead to undesirable sector charging. From the model it could be suggested that charging of material at any given chute angle should always occur for more than a single revolution to minimise potential sector charging. There was good agreement between the model described in this paper and a trajectory/layer model from previous full scale tests.[1,20]

However, this is a 'trajectory only' model, where material behaviour on the chute influenced by angle of repose effects is important. The behaviour of material once it impacts the bulk material at the top of the furnace is not simulated. Future work will include this effect to better understand the relationships between chute design and the formation of layers within the blast furnace.

6. Conclusions

- A numerical model of blast furnace charging has been developed and used to study the charging of a blast furnace for three different chute designs: rock box, straight and hybrid.
- In this work full-scale results are presented although there are lower limits on particle size to achieve useful run times.
- For the historical 'ledge' charging strategy the use of the hybrid chute design is predicted to provide homogeneous charge distributions.
- For the modern charging strategies which attempt to produce a 'chimney' burden distribution the rock box chute design is predicted to produce the most homogeneous charging patterns.
- Other lower spread chute designs (straight and hybrid) are predicted to deliver burden material with a less homogeneous distribution.
- Subsequent granular flow effects near the surface might improve this inhomogeneous delivery of material and form the basis of future work.
- The effects of using non-spherical particles, while numerically more challenging, is also the subject of Tata-sponsored current research work. [21]

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	Value		
Time step (s)	1.0×10^{-4}		
Materials properties	*Coke*	*Pellets*	*Sinter*
Spring constant ($kg\cdot m\cdot s^{-2}$)	16000	2000	2000
Poisson's ratio	0.1	0.3	0.3
Coefficient of restitution	0.01	0.01	0.01
Particle-Particle/Wall Sliding Coefficient	0.8	0.8	0.8
Particle-Particle/Wall Rolling Coefficient	0.3	0.1	0.1
Particle-Particle/Wall Twisting Coefficient	0.3	0.1	0.1
Particle-Particle/Wall Rolling dampening	1.5	1.5	1.5
Particle-Particle/Wall Twisting dampening	1.5	1.5	1.5
Density $kg.m^{-3}$	1150	4000	1970
Largest particles radius (m)	0.035	0.075	0.06
Smallest particle radius (m)	0.0125	0.075	0.0125

Table 1. Parameters used for coke, sinter and pellet charging simulations.

	Straight	*Hybrid*	*Rock box*
Series 1	Coke D1	Coke D1	Coke D1
Series 2	Coke D5	Coke D5	Coke D5
Series 3	Pellets D2	Pellets D2	Pellets D2
Series 4	Pellets D4	Pellets D4	Pellets D4
Series 5		Ledge charging 1 (coke) Ledge charging 2 (sinter) Ledge charging 3 (coke)	

Table 2. Burden material and charging sequences for the series of simulations 1 to 5.

Chute angle (degrees)	44.5	41.9	38.3	34.6	31.0	27.4	23.8	20.1	16.5	10.0	0.0
Coke D1 (% tot. weight)	28	9	9	9	9	0	9	9	0	18	0
Coke D5 (% tot. weight)	20	10	10	10	10	10	10	0	0	10	10

Table 3. Coke charging sequences D1 and D5. Standard coke charge is 16t, coke bulk density 0.55 $t.m^{-3}$, volume ~ 29 m^3, discharge rate 0.2 $t.s^{-1}$, total charge time 80 s.

Chute angle (degrees)	44.5	41.9	38.3	34.6	31.0	27.4	23.8	20.1	16.5	10.0
Ferrous D2 (% tot. weight)	12	13	12	13	12	13	12	13	0	0
Ferrous D4 (% tot. weight)	15	14	14	14	14	0	14	0	15	0

Table 4. Ferrous pellet charging sequences D2 and D4. Standard pellet charge is 42t, pellet bulk density 1.8 $t.m^{-3}$, volume ~ 23 m^3, discharge rate 0.7 $t.s^{-1}$, total charge time 60 s.

Chute angle (degrees)	44.1	37.5	35.1	32.5	28.7	24.2
Ledge charging 1 Coke (% tot. weight)	-	15	20	20	25	20
Ledge charging 2 Sinter (% tot. weight)	20	20	-	20	20	20
Ledge charging 3 Coke (% tot. weight)	25	20	20	20	15	-

Table 5. Series 5 ledge charging sequences. For coke charging sequences 1 and 3: Charge is 18.8t, coke bulk density 0.55 $t.m^{-3}$, volume ~ 34 m^3, discharge rate 0.2 $t.s^{-1}$, total charge time 94 s, (particle size distribution, radius 0.06-0.05m 2.7%, 0.05-0.04m 3.8% and 0.04-0.03m 93.5%). For ferrous sinter charging sequence 2: Charge is 70t, sinter bulk density 1.97 $t.m^{-3}$, volume ~ 35 m^3, discharge rate 0.7 $t.s^{-1}$, total charge time 100 s, (particle size distribution, radius 0.06-0.02m 0.5% and 0.02-0.0125m 0.95%).

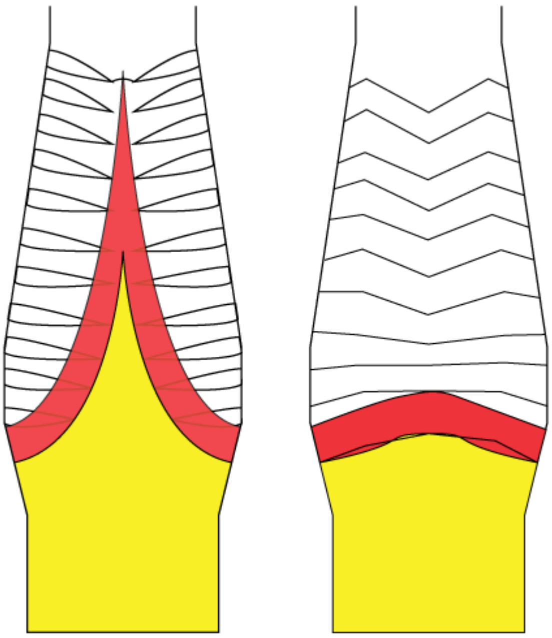


Figure 1. Schematic diagram of Chimney (left) and Ledge (right) approaches to blast furnace charging.

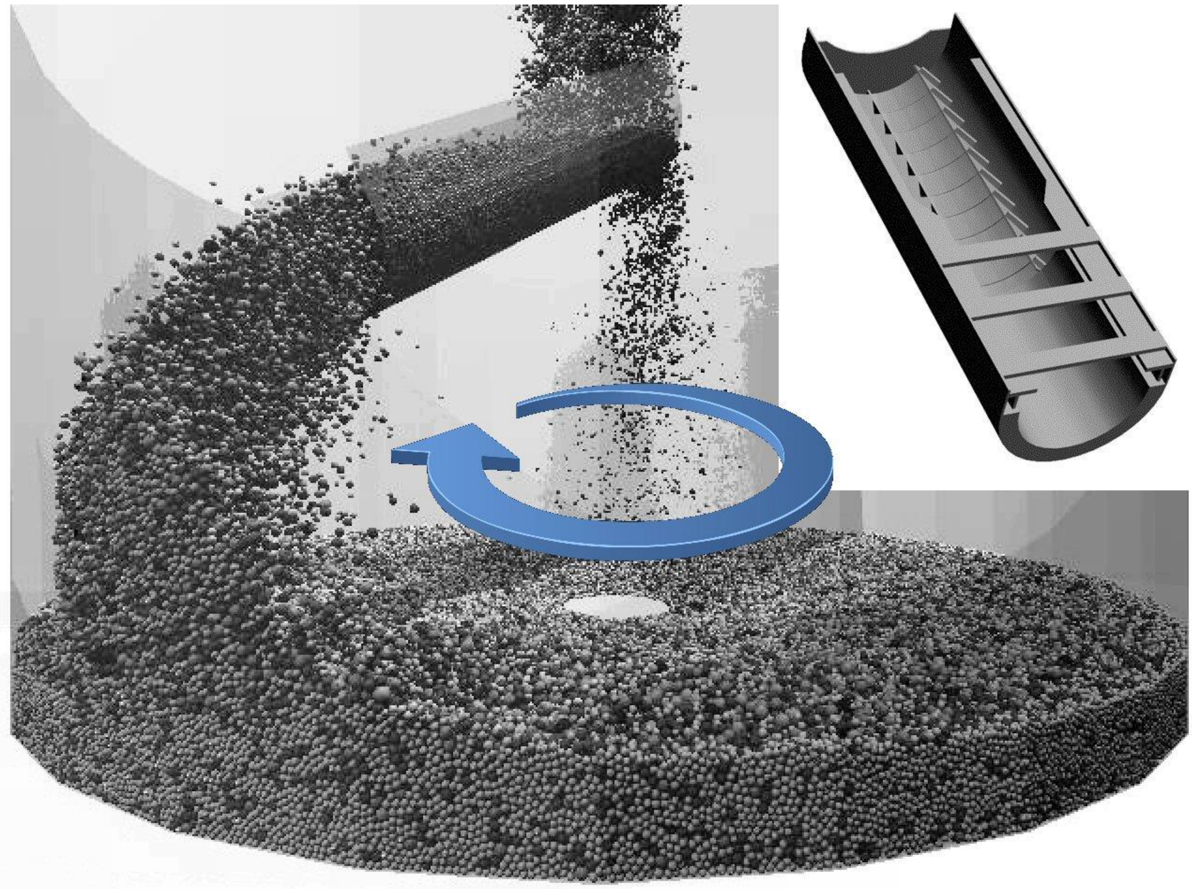


Figure 2. Full scale DEM simulation of blast furnace charging using a hybrid chute (shown in top-right insert).

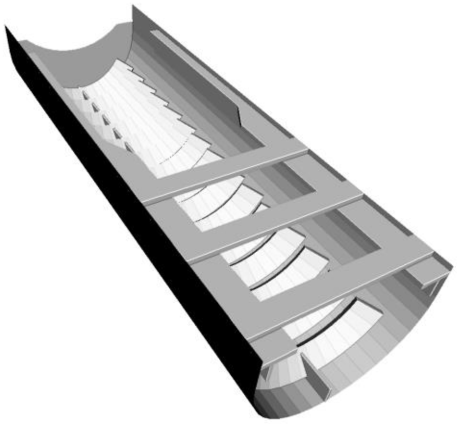


Figure 3. Rock box chute design.

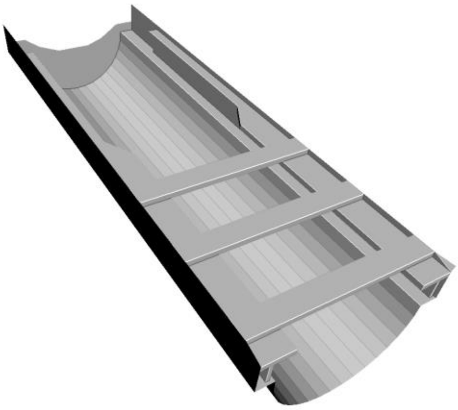


Figure 4. Straight chute design.

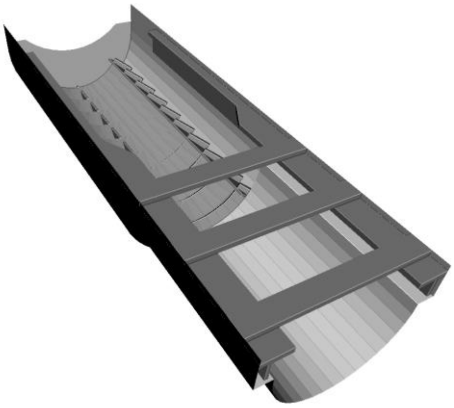


Figure 5. Hybrid chute design.

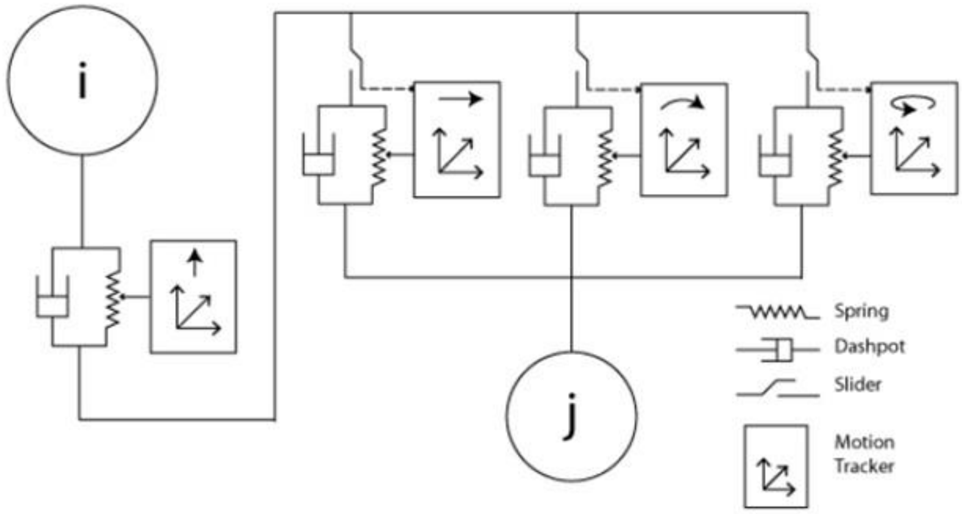


Figure 6. DEM force model for interaction of two particles i and j.

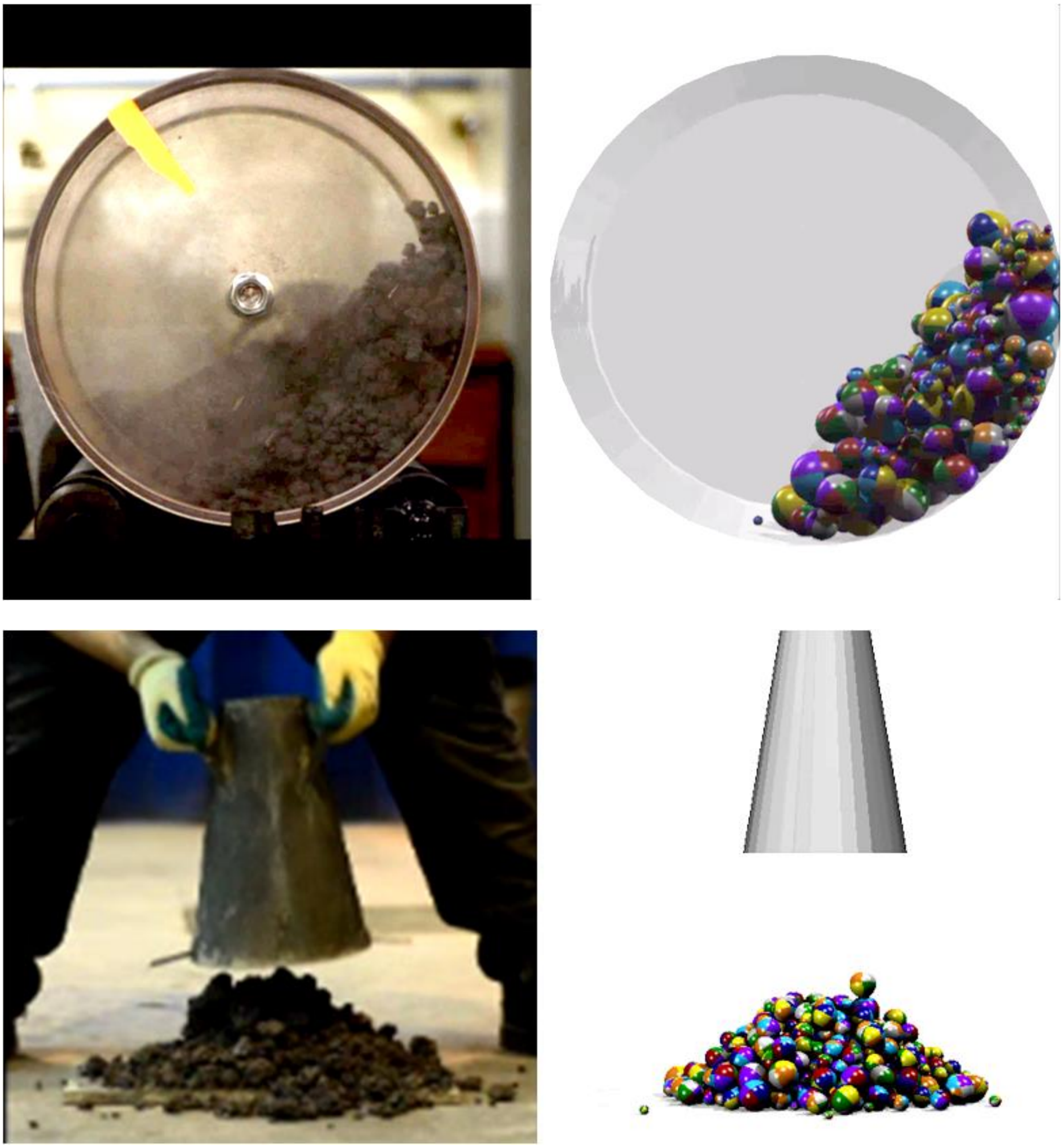


Figure 7. Validation experiments for burden materials showing rotating drum sinter experiment (top left), DEM simulation of rotating drum (top right), coke slump test (bottom left) and DEM simulation of slump test (bottom right).

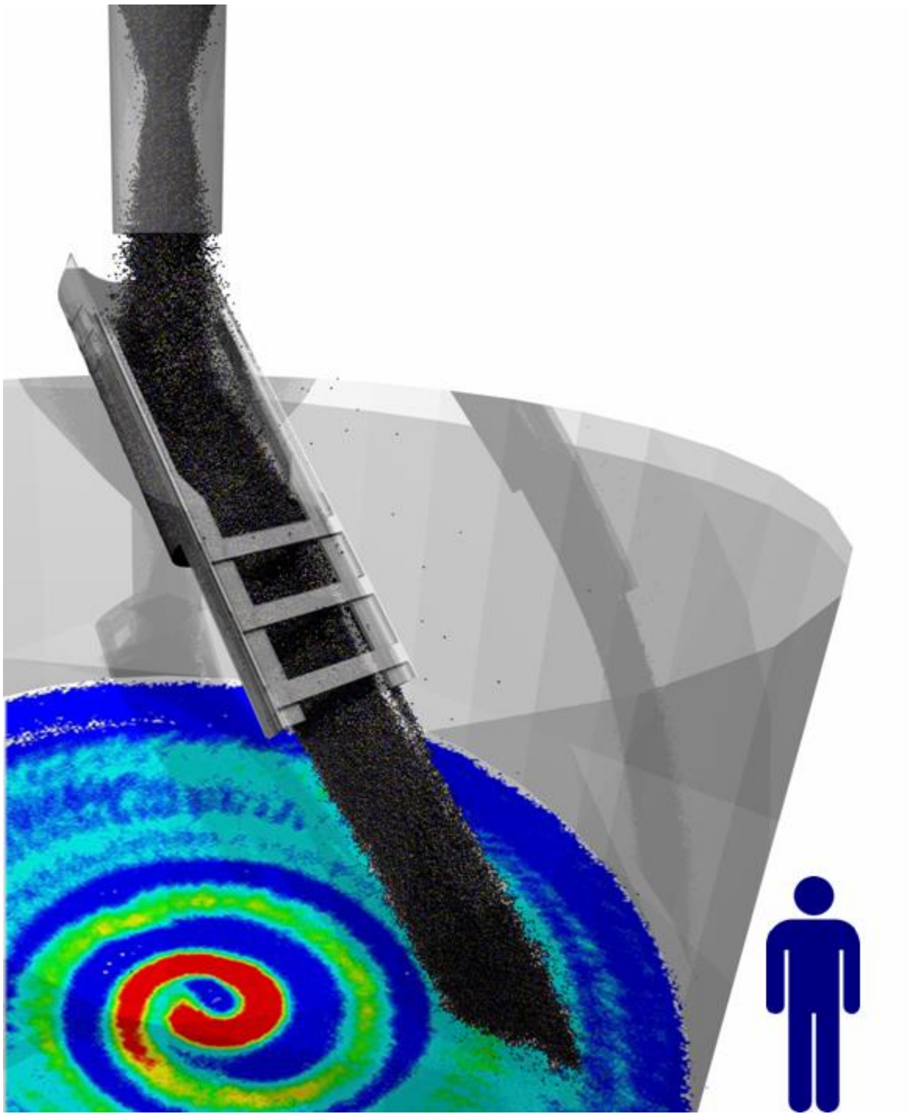
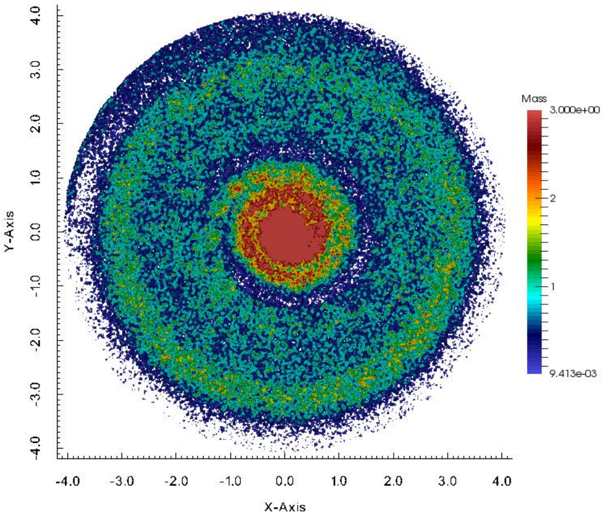
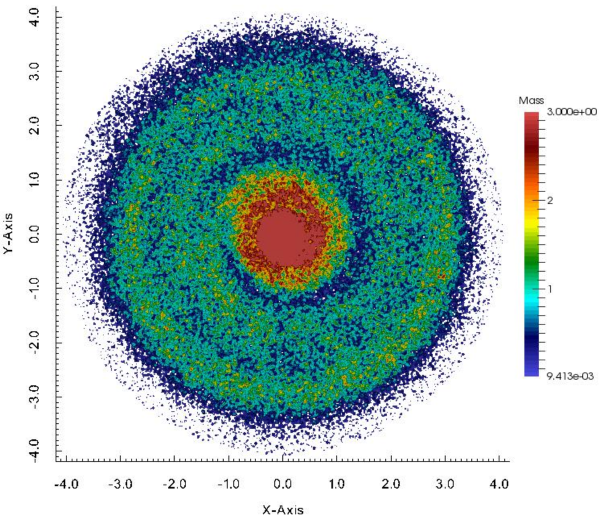


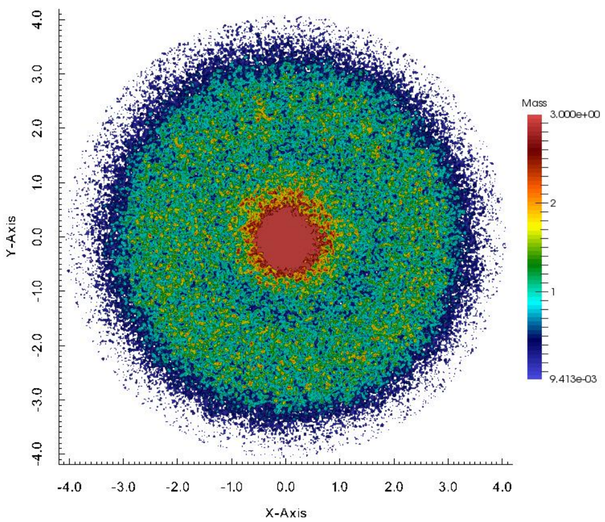
Figure 8. Schematic diagram showing the position of the plane where the mass distribution of burden passing through the plane is captured (furnace diameter 8.2m at this throat section).



(a)

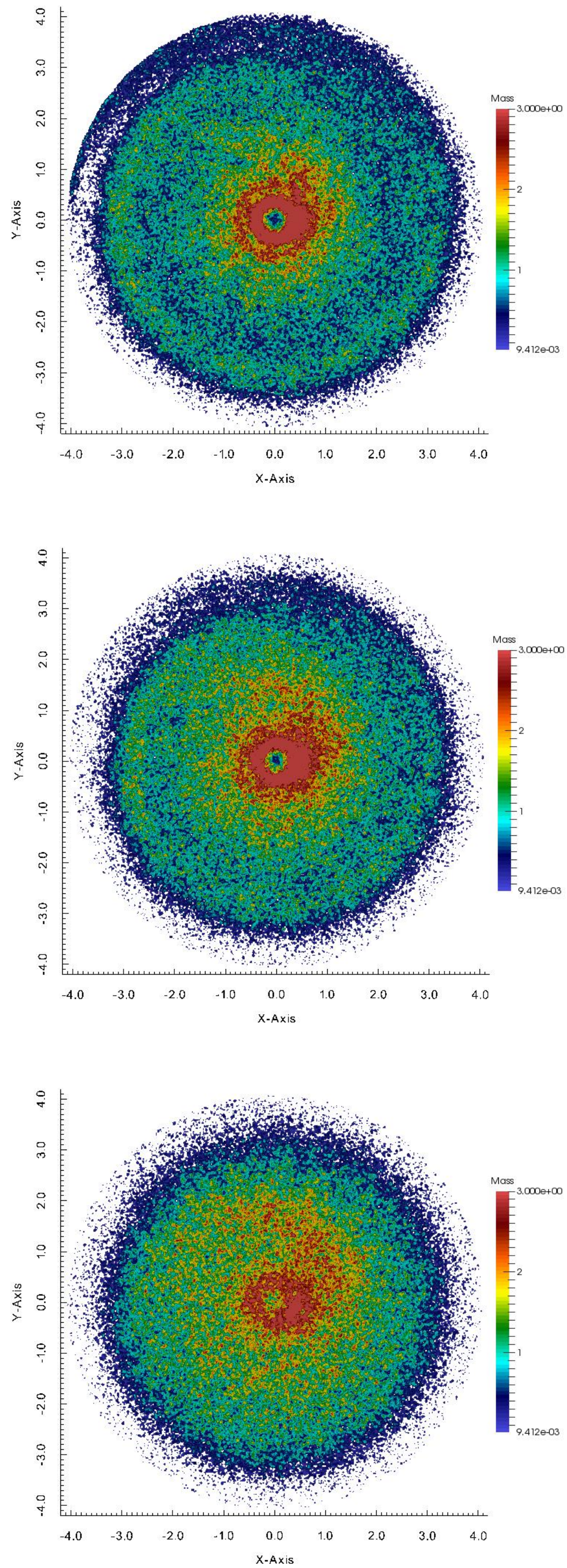


(b)



(c)

Figure 9. Total mass delivery distribution D1 coke results for (a) straight chute, (b) hybrid and (c) rock box (axes in m).

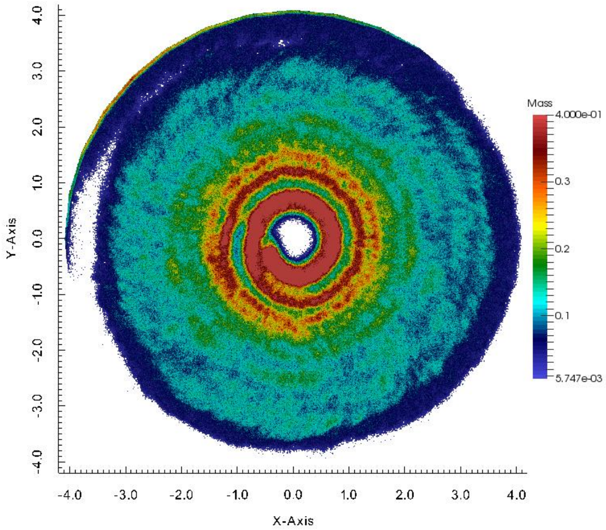


(a)

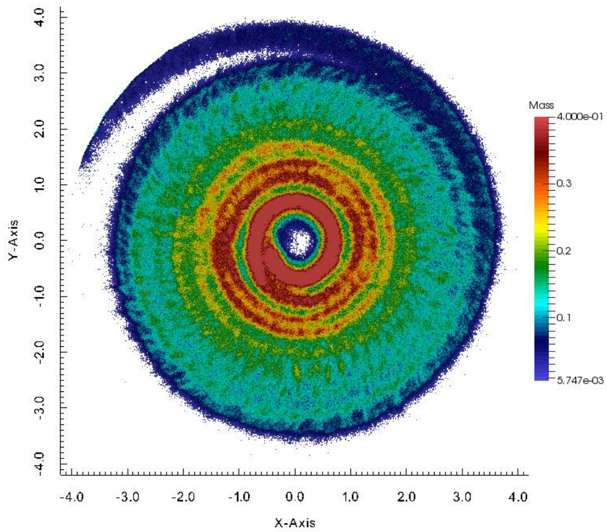
(b)

(c)

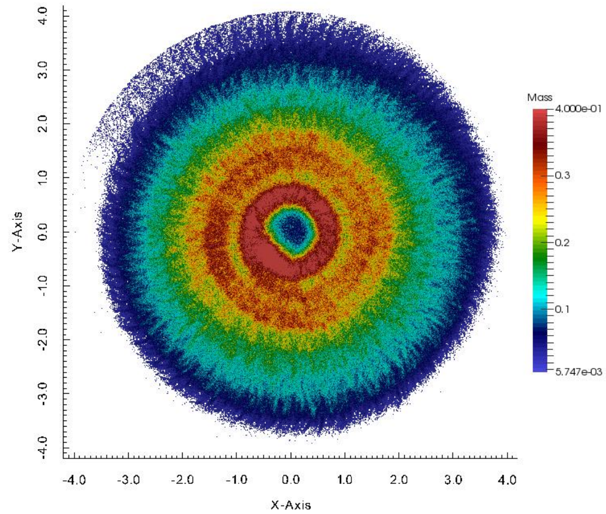
Figure 10. Total mass delivery distribution D5 coke results for (a) straight chute, (b) hybrid and (c) rock box (axes in m).



(a)

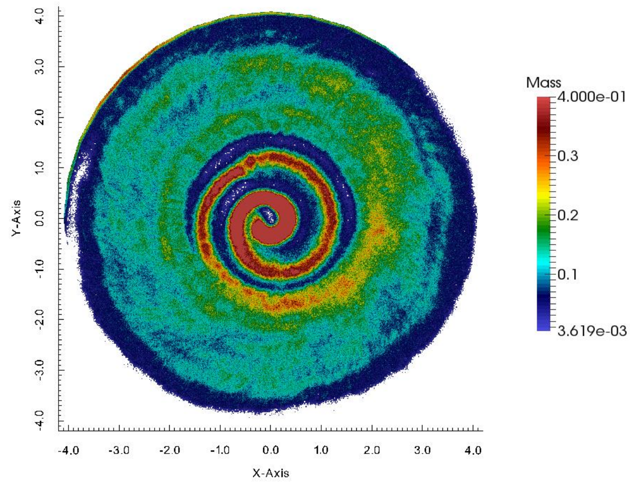


(b)

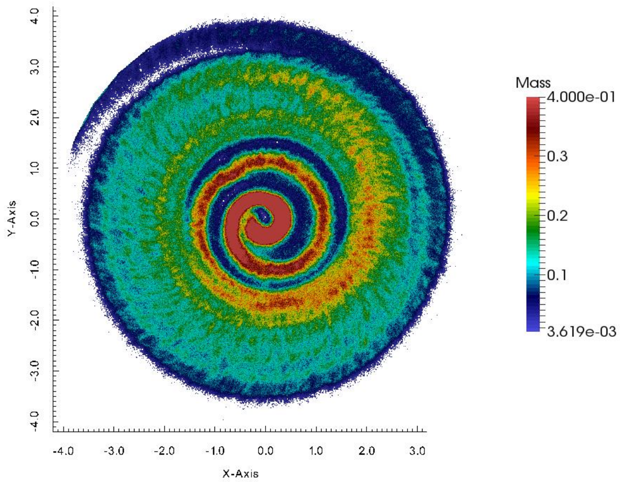


(c)

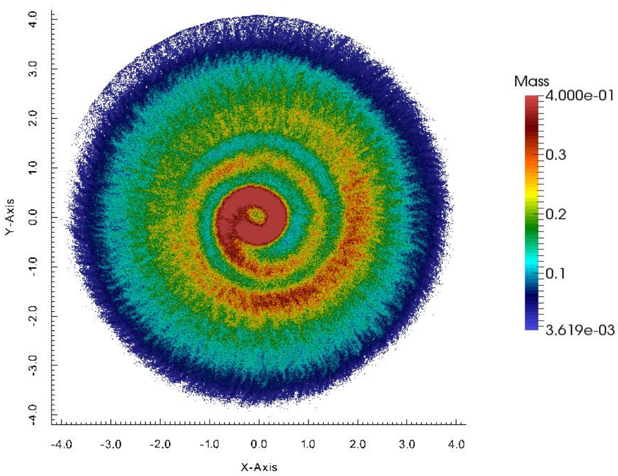
Figure 11. Total mass delivery distribution D2 pellet results for (a) straight chute, (b) hybrid and (c) rock box (axes in m).



(a)

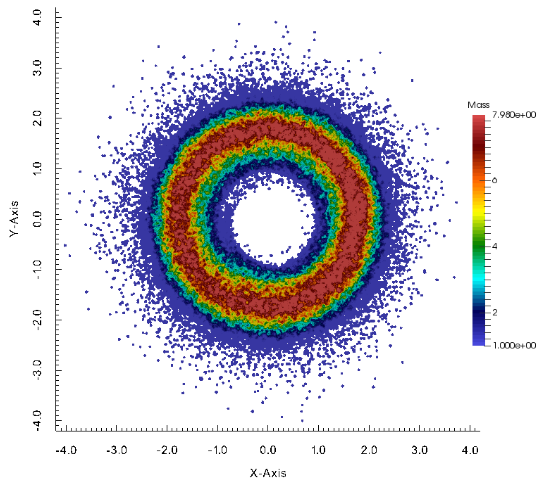


(b)

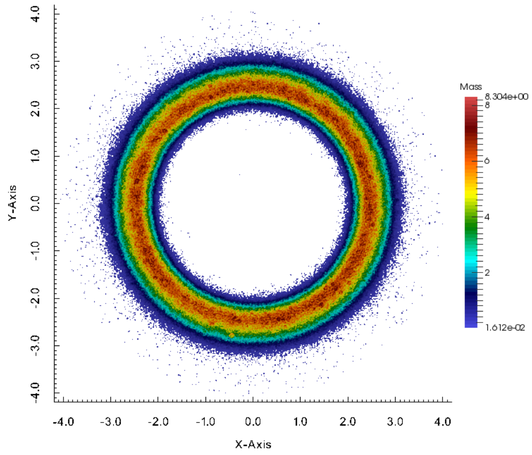


(c)

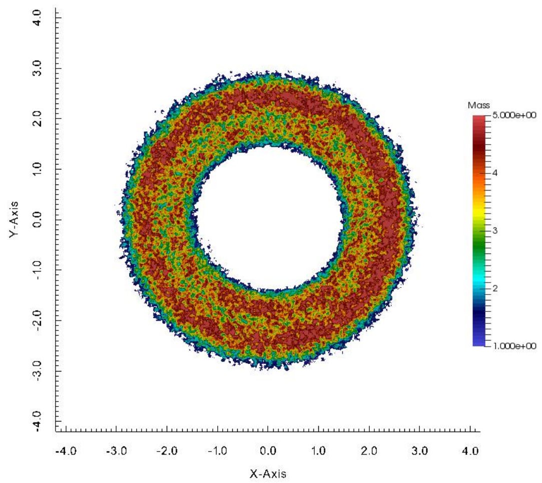
Figure 12. Total mass delivery distribution D4 pellet results for (a) straight chute, (b) hybrid and (c) rock box (axes in m).



(a)



(b)



(c)

Figure 13. Total mass delivery distribution for hybrid chute design. (a) Ledge charging pattern 1, coke (b) Ledge charging pattern 2, sinter (c) Ledge charging pattern 3, coke.