Insights into the segregation in the blast furnace charging system: from the stockhouse to top hoppers

A. Hadi, Y. Pang, A. Adema, J. van der Stel, D. Schott

Segregation in the blast furnace (BF) charging system is a significant challenge, as it can negatively affect the burden permeability and reduce BF efficiency. The discrete element method (DEM) is a valuable tool to gain insights into segregation dynamics in the BF. While previous DEM studies have extensively investigated segregation in the BF, the majority of them used the top hoppers as the starting point and assumed a pre-determined iron ore mixture composition (usually fully mixed state) within the top hopper. Considering the fact that the final segregation on the BF burden is significantly influenced by the degree of the segregation within the top hopper, it is crucial to precisely determine the degree of mixing of iron ore pellets and sinter within the hopper. In this study, we model the BF charging process from the stockhouse (i.e. weighing bunkers) until the top hopper at the industrial scale, aiming to elucidate how previous handling steps can affect the mixture composition within the hopper. Our findings reveal that the degree of mixing of pellets and sinter within the weighing bunkers (WBs) significantly influences the quality of mixing within the top hopper. Under the current practice where each materials are charged into separate WB, they are significantly segregated in the top hopper. We also demonstrated that mixing pellets and sinter before charging them into the WBs, can significantly reduce segregation within the hopper. The results of this study enhance our understanding of the segregation phenomenon in the BF charging system, providing insights that can be used for optimising the charging process.

KEYWORDS: SEGREGATION, BLAST FURNACE, DEM, GRANULAR MATERIALS, DEM UPSCALING, PELLETS AND SINTER

INTRODUCTION

Segregation of granular materials is often viewed as an undesirable occurrence that should be controlled or minimised due to its negative impact on processes and/or products [1]. In blast furnace, segregation can adversely affect the distribution of materials on the burden surface, which in turn has a detrimental effect on bed permeability [2]. This affected permeability leads to inconsistencies in pressure drop, causing inefficient use of reductant gas and resulting in both economic and environmental consequences [3]. Therefore, it is crucial to investigate and understand segregation within the blast furnace processes. Conducting experiments or in-situ measurements of segregation in the blast furnace charging system is costly and/or impractical due to the large-scale equipment and harsh environment. Alternatively, the discrete element method (DEM), a helpful tool for modelling granular materials, can be employed to gain insight into segregation in blast furnace.

Ahmed Hadi, Yusong Pang, Dingena Schott
Delft University of Technology, the Netherlands

Allert Adema, Jan van der Stel
Tata Steel Europe, the Netherlands

Many DEM studies have recently investigated blast furnace segregation [4,5]. However, the majority of these studies have focussed on segregation happening after the top hopper, i.e. on the chute and the blast furnace burden [6,7]. Additionally, they have mostly studied the size segregation of individual materials such as pellets, sinter or coke, with only a few addressing the segregation of multiple materials, referred to as component segregation [1]. Furthermore, most of these studies employed down-scaled dimensions of the blast furnace geometry to reduce DEM computational time. In this study, we address these shortcomings by modelling the real-scale blast furnace charging process from the stockhouse to the top hopper. We mainly focus on the pellets and sinter as two main ore materials and study their mixing/segregation behaviour.

METHODS

Discrete element method (DEM)

We used DEM with Hertz-Mindlin (no-slip) [8] contact model with an elastic-plastic spring-dashpot rolling friction model (referred to as type C in Ai et al. [9]). This contact model has been successfully employed for modelling iron ore pellets and sinter in past studies [10,11]. Detailed information and equations of the contact model can be found in the relevant literature [8,9,12]. We employed the commercial software EDEM V2022.3 for DEM simulations, which were conducted on the DelftBlue supercomputers [13].

Materials

We modelled iron ore pellets and sinter as two main components of ore mixtures charged into the blast furnace.

To reduce the computational time, we used spheres to model the particle shape of both pellets and sinter. The size distribution of pellets and sinter, measured using sieves, is provided in Tab. 1. A comprehensive list of all DEM parameters used is mentioned in our previous study [14].

Tab. 1 – Size distribution of pellets and sinter used in this study.

Size Distribution of pellets and sinter		
Size range	**Pellets**	**Sinter**
5.6-8 (mm)	-	36.37%
8-10 (mm)	-	23.13%
10-12.5 (mm)	48%	17.61%
12.5-16 (mm)	52%	13.45%
16-20 (mm)	-	5.08%
> 25 (mm)	-	4.36%

Geometries and the charging process

Fig. 1 shows the geometries used in this study to simulate the charging system of the blast furnace at Tata Steel. The system consists of two weighing bunkers (WBs) for storing pellets and sinter. During the charging process, approximately 20 tons of pellets and 12 tons of sinter are loaded into the weighing bunkers. The outlets of these WBs are opened simultaneously, in a controlled way to ensure that both are emptied at the same time. In the actual process, the filled skip car then moves up an inclined rail. Since we anticipate negligible segregation during this step, we omitted the simulation of the skip car moving up and positioned it directly at the top location where it starts to tilt. The skip car is then tilted and the mixture of pellets and sinter are charged into the top funnel. The mixture passes through a series of equipment, including a semi-cylinder chute, and finally into one of the top hoppers. This entire process is repeated for the second skip car.

Quantifying segregation

We used relative standard deviation (RSD), a grid-dependent segregation index, to quantify segregation. First, the whole domain of the mixture is divided into a number of bins, denoted as 'm'. Then, the mass ratio of one of the components (e.g. pellets) is measured within each bin (C_{Pm}). Next, the mean (μ) and the standard deviation (σ) of C_{Pm}s are calculated. Finally, RSD is computed as:

$$RSD = \frac{\sigma}{\mu} \qquad (1)$$

A lower RSD value indicates better mixing, with an RSD close to zero showing negligible segregation.

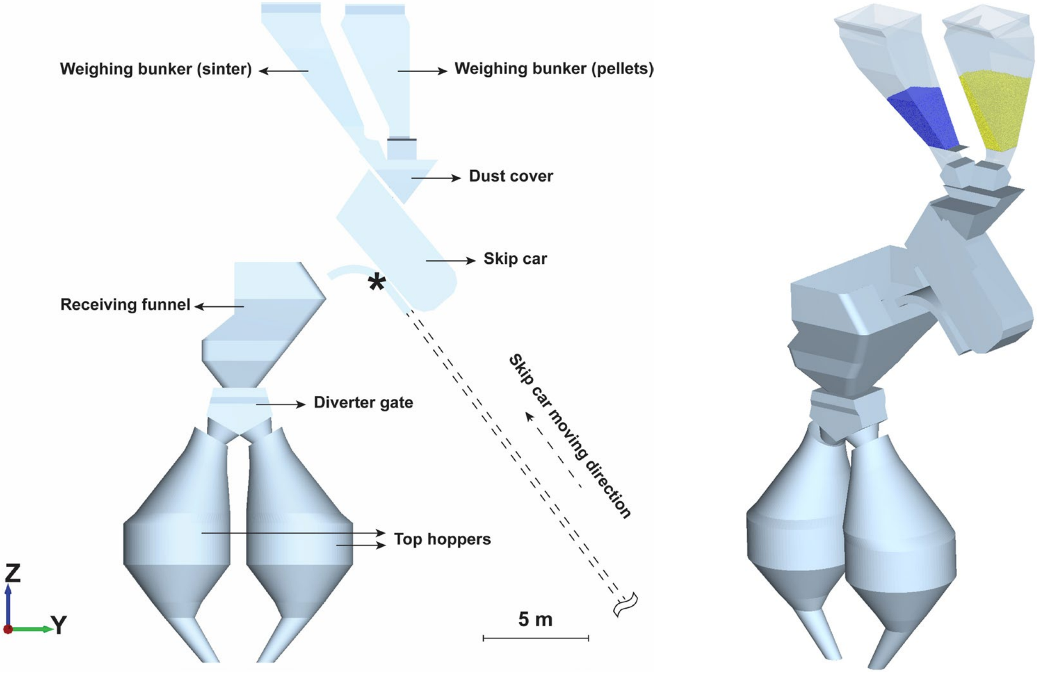
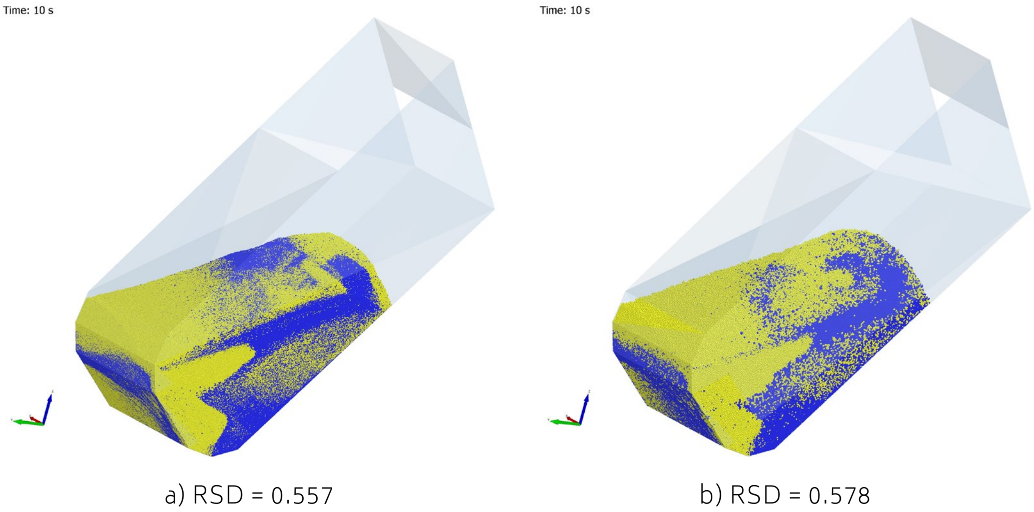


Fig.1 -a) The geometry model used in this study. For practical reasons, the WBs and the skip car are placed at the location (*), while in practice they are located at the bottom, and the skip car moves up in the mentioned direction. b) 3-D view of the geometries. Yellow and blue particles represent pellets and sinter, respectively.

RESULTS AND DISCUSSION

Scaling up the particle size

Considering the dimensions of blast furnace equipment and the large number of particles involved, DEM simulations can be computationally expensive. To reduce computational time, we upscaled the particle size by a scaling factor (SF) of two. To ensure that this scaling does not affect the segregation results, we modelled the first charging step (i.e. from weighing bunkers to the skip car) using both original and upscaled particle sizes. As shown in Fig. 2, the comparison reveals that there is no significant difference in the degree of mixing between the two from both qualitative and quantitative perspectives, with only ~3.7% change in RSD. However, the computational time for modelling only this charging step was decreased from 25 hr to 1.5 hr. Therefore, we proceeded with the upscaled particles for the current study.

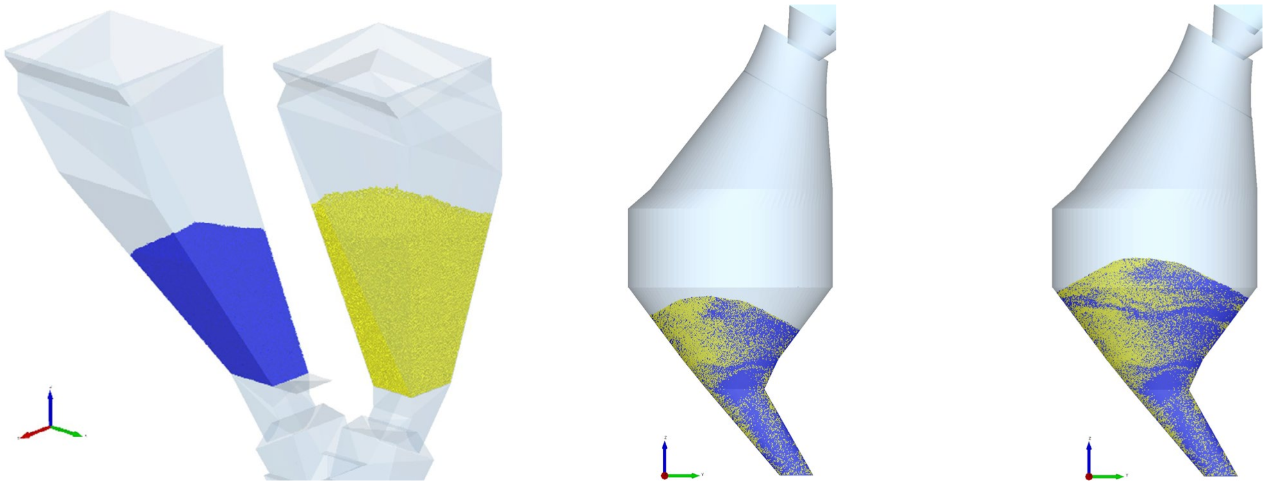


a) RSD = 0.557 b) RSD = 0.578

Fig.2 - Qualitative comparison of the degree of mixing within the skip car between a) original size, and b) upscaled particles with SF of 2.0. Yellow and blue particles represent pellets and sinter, respectively.

Scenario 1: Current practice

In the current practice at Tata Steel, individual components —pellets and sinter— are charged separately into weighing bunkers (WBs), as shown in Fig. 3a. During the simultaneous discharging of these bunkers, pellets and sinter are mixed to some extent. However, Fig. 2b illustrates that the majority of the materials within the skip car remain segregated, resulting in a high RSD of 0.578. Upon emptying the skip car into the receiving funnel and then the top hopper, the materials are expected to become more mixed. Fig. 3b and 3c show the materials within the hopper after charging the first and second skip cars, respectively. A reduced RSD for the mixture within the top hopper indicates that pellets and sinter become more mixed as they are charged from the skip car into the hopper. Nevertheless, it can be observed that materials are still segregated, with more sinter accumulating on the right side of the hopper. This indicates that the assumption of pellets and sinter having a good degree of mixing within the top hopper is incorrect. Although the current practice assumes that pellets and sinter mix through the charging process, the materials mostly remain segregated.



a) b) RSD = 0.415 c) RSD = 0.393

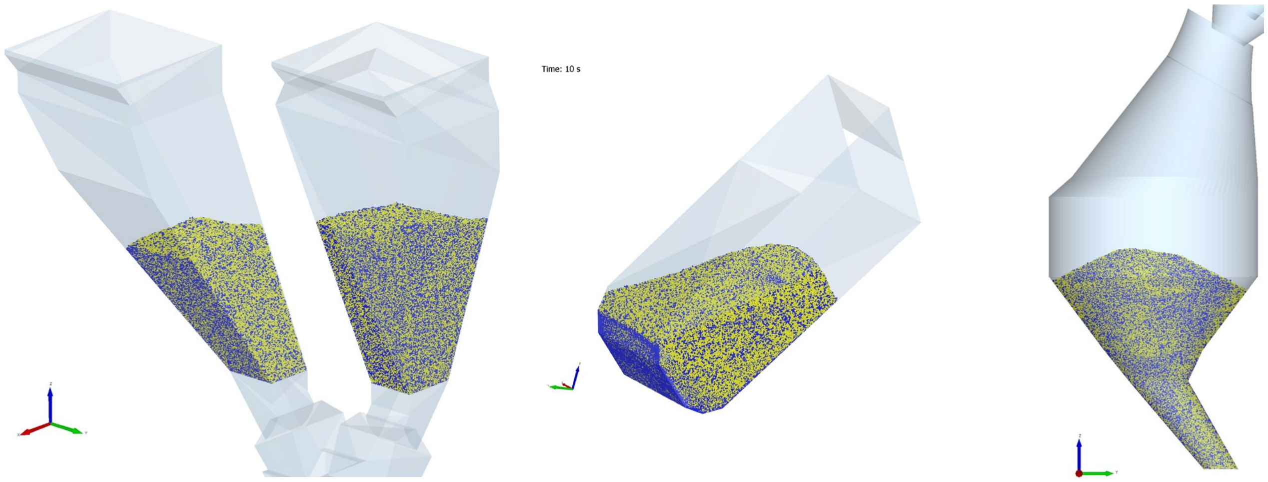
Fig.3 - a) Weighing bunkers filled with pellets (yellow particles) and sinter (blue particles) under the current practice. Materials within the hopper after b) the first and c) the second skip car charged in.

Scenario 2: Mixed configuration in WBs

We demonstrated in our previous study that negligible segregation occurs downstream if pellets and sinter are perfectly mixed upstream [15]. Therefore, we conclude that maximising the mixing of pellets and sinter in the upstream locations (e.g., within the WBs) results in minimal segregation throughout the charging process. A potential strategy is to mix the materials before charging them into the skip car. To investigate and confirm this, we started from a perfect mixing of pellets and sinter within the WBs and subsequently, simulated the entire charging process. Fig. 4b and 4c present the quality of mixing within the skip car and the top hopper, confirming that minimal segregation occurs when materials are perfectly mixed, and they mostly remain mixed within the top hopper.

CONCLUSION

This study investigated the mixing/segregation dynamics of pellets and sinter within the blast furnace charging system, focussing on the charging steps from the stockhouse to the top hopper. Our findings reveal that under the current practice at Tata Steel, pellets and sinter tend to mostly remain segregated within the top hopper due to insufficient mixing of materials during discharging from the weighing bunkers into the skip car. To address this issue, we explored an alternative scenario where pellets and sinter were perfectly mixed within the skip car. Remarkably, this approach virtually eliminated the segregation during the charging process. This underscores the critical need for strategies aimed at improving the initial degree of mixing of pellets and sinter to maintain a well-mixed mixture throughout the charging process. Further research could focus on simulating and exploring various strategies for mixing the materials within the weighing bunkers. Implementing these strategies can potentially optimise the blast furnace operations and achieve a higher efficiency of the process.



a) RSD = 0.029 b) RSD = 0.071 c) RSD = 0.094

Fig.4 - a) Weighing bunkers filled with a perfect mixture of pellets (yellow particles) and sinter (blue particles), b) mixture within the skip car, and c) materials within the hopper after the second skip car charged in.

ACKNOWLEDGEMENT

This research was carried out under project number T18019 in the framework of the Research Program of the Materials innovation institute (M2i) (www.m2i.nl) supported by the Dutch government.

REFERENCES

[1] A. Hadi, R. Roeplal, Y. Pang, D.L. Schott, DEM Modelling of Segregation in Granular Materials: A Review, KONA Powder Part. J. (2023). https://doi.org/10.14356/kona.2024017.

[2] Y. Yu, H. Saxén, Experimental and DEM study of segregation of ternary size particles in a blast furnace top bunker model, Chem. Eng. Sci. 65 (2010) 5237–5250. https://doi.org/10.1016/j.ces.2010.06.025.

[3] T. Bhattacharya, J.J. McCarthy, Chute flow as a means of segregation characterization, Powder Technol. 256 (2014) 126–139. https://doi.org/10.1016/j.powtec.2014.01.092.

[4] R. Roeplal, Y. Pang, A. Adema, J. van der Stel, D. Schott, Modelling of phenomena affecting blast furnace burden permeability using the Discrete Element Method (DEM) – A review, Powder Technol. 415 (2023). https://doi.org/10.1016/j.powtec.2022.118161.

[5] J. Chen, H. Zuo, Q. Xue, J. Wang, A review of burden distribution models of blast furnace, Powder Technol. 398 (2022). https://doi.org/10.1016/j.powtec.2021.117055.

[6] S. Wu, M. Kou, J. Xu, X. Guo, K. Du, W. Shen, J. Sun, DEM simulation of particle size segregation behavior during charging into and discharging from a Paul-Wurth type hopper, Chem. Eng. Sci. 99 (2013) 314–323. https://doi.org/10.1016/j.ces.2013.06.018.

[7] L. He, X. Jiang, H. An, H. Zheng, Q. Gao, F. Shen, Effects of pellet ratio on the burden movement and distribution characteristics in the BF throat, Powder Technol. 432 (2024). https://doi.org/10.1016/j.powtec.2023.119130.

[8] H.P. Zhu, Z.Y. Zhou, R.Y. Yang, A.B. Yu, Discrete particle simulation of particulate systems: Theoretical developments, Chem. Eng. Sci. 62 (2007) 3378–3396. https://doi.org/10.1016/j.ces.2006.12.089.

[9] J. Ai, J.F. Chen, J.M. Rotter, J.Y. Ooi, Assessment of rolling resistance models in discrete element simulations, Powder Technol. 206 (2011) 269–282. https://doi.org/10.1016/j.powtec.2010.09.030.

[10] A. Tripathi, V. Kumar, A. Agarwal, A. Tripathi, S. Basu, A. Chakrabarty, S. Nag, Quantitative DEM simulation of pellet and sinter particles using rolling friction estimated from image analysis, Powder Technol. 380 (2021) 288–302. https://doi.org/10.1016/j.powtec.2020.11.024.

[11] A. Chakrabarty, R. Biswas, S. Basu, S. Nag, Characterisation of binary mixtures of pellets and sinter for DEM simulations, Adv. Powder Technol. 33 (2022). https://doi.org/10.1016/j.apt.2021.11.010.

[12] C.M. Wensrich, A. Katterfeld, Rolling friction as a technique for modelling particle shape in DEM, Powder Technol. 217 (2012) 409–417. https://doi.org/10.1016/j.powtec.2011.10.057.

[13] L.F. Viera Valencia, D. Garcia Giraldo,済無No Title No Title No Title, Angew. Chemie Int. Ed. 6(11), 951–952. 2 (2019). https://www.tudelft.nl/dhpc/ark:/44463/DelftBluePhase1.

[14] A.H. Hadi, Y. Pang, D.L. Schott, Calibration of DEM Parameters for Multi-Component Segregation, in: ICBMH 2023 14th Int. Conf. Bulk Mater. Storage, Handl. Transp., 2023.

[15] A. Hadi, H. Shi, Y. Pang, D. Schott, Identification of dominant DEM parameters for multi-component segregation during heap formation, hopper discharge and chute flow, Powder Technol. (2024) 119985.

TORNA ALL'INDICE >