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Cross Flow Turbine to Reduce Size Segregation Effects in Storage Processes

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ABSTRACT In many applications a constant particle size distribution is desired. Various effects lead to size segregation during storage processes. Especially during bunker filling segregation effects are noticed, which are further intensified by possible core flow effects. In this work discrete element simulations were performed to analyze a bunker used for storage of blast furnace sinter, which is filled with a discharging belt conveyor, whereby significant segregation effects are noticed. Several devices including solid state material turbines to reduce segregation during bunker filling were evaluated using DEM. A cross flow turbine is presented, which is proven to significantly reduce segregation effects during bunker filling. The results show a more evenly distributed bunker outflow in terms of particle size. Because sinter is a very abrasive material, the expected wear at the turbine was also estimated with DEM. As the turbine could also be used for energy recovery in other applications, the power output was also investigated. Additionally, the particle breakage due to the cross flow turbine is evaluated in this case. Therefore, a newly developed breakage model for DEM is used. The model is based on a probabilistic particle replacement with voronoi-tessellated fragments. The validated breakage model allows high accuracy in prediction of fragment size distribution. Fragments are further breakable, which allows simulation of processes with several damaging effects. The breakage model was calibrated with a specially developed single particle impact tester for rapid analysis of breakage characteristics of bulk materials.

1. INTRODUCTION

For storage or buffering mostly bunkers are used. Particle size segregation effects at the bunker outflow lead to fluctuations in particle size distribution. In most applications and for their following processes, an evenly distributed bunker discharge is desired in terms of particle size distribution. This especially applies to blast furnace sinter bunkers as a constant particle size distribution for blast furnace operation is needed to ensure a sufficient gas flow.

This study was conducted within the RFCS-project MinSiDeg, which received funding from the European Union and was performed by the University of Leoben and several industry partners from Austria and Germany. One objective in MinSiDeg was to develop or further develop innovative conveying and storage equipment in order to reduce degradation and segregation effects during conveying and storage processes of blast furnace sinter. One of these devices is the solid state material turbine, which was originally developed and patented in [1] and was described in [2–4] for energy recovery. In this work the solid state material driven turbine was further developed and optimized to reduce segregation effects. This contribution is an updated and extended version of [5] and was partly presented in [6] and [7].

2. SEGREGATION EFFECTS DURING BUNKER FILLING

Bunkers are mostly used for storage or buffering. Particle size segregation effects at the bunker outflow lead to fluctuations in particle size distribution. In most applications and for their following processes, an evenly-distributed bunker discharge is desired in terms of particle size distribution. This especially applies to blast furnace sinter bunkers as a constant particle size distribution for blast furnace operation is needed to ensure a sufficient gas flow.

Significant segregation effects during bunker filling mainly occur due to the following two effects. Due to vibrations during transport by conveyor belt, small particles accumulate at the bottom and large particles at the top of the bulk material heap in the conveyor belt. Thus, the large particles have a different trajectory than the small particles when discharged. Depending on the belt incline and speed, at discharge the large particles could have a higher velocity than the small particles due to the greater distance of the large particles to the center of the discharge pulley. This could lead to an accumulation of large particles in the conveying direction and an accumulation of small particles against the conveying direction of the discharging conveyor belt in the bunker [8].

The second segregation effect is noticed every time a bulk material pile is formed. As larger particles have a greater forward momentum than smaller particles, the coarse material continues moving down the side of the pile more than the fine material. The material that tumbles down the slope of a pile is called overrun. Larger particles tend to roll down the entire length of the slope and fine particles tend to settle into the side of the pile. This effect of overrun causes the outer and bottom zones of the pile to consist of coarser material, while the inner and upper zones of the pile consist of more fine material [8].

3. CURRENT STATE

The current state at a steel manufacturer in Austria was investigated. Blast furnace sinter is stored in square-shaped bunkers with filling levels of up to 600t, which are filled by conveyor belts with a mass flow of 300t/h and an almost constant particle size distribution (Figure 1a). Low filling levels lead to high drop heights, which is assumed to be one of the main reasons for material degradation. In Figure 1b) the pile forms in a dip, which is caused by the core flow effect during previous discharging. As described in chapter 2, the outer and bottom zones of the pile consist of large particles, which leads to an accumulation of coarse material in the outer zones in the entire bunker.

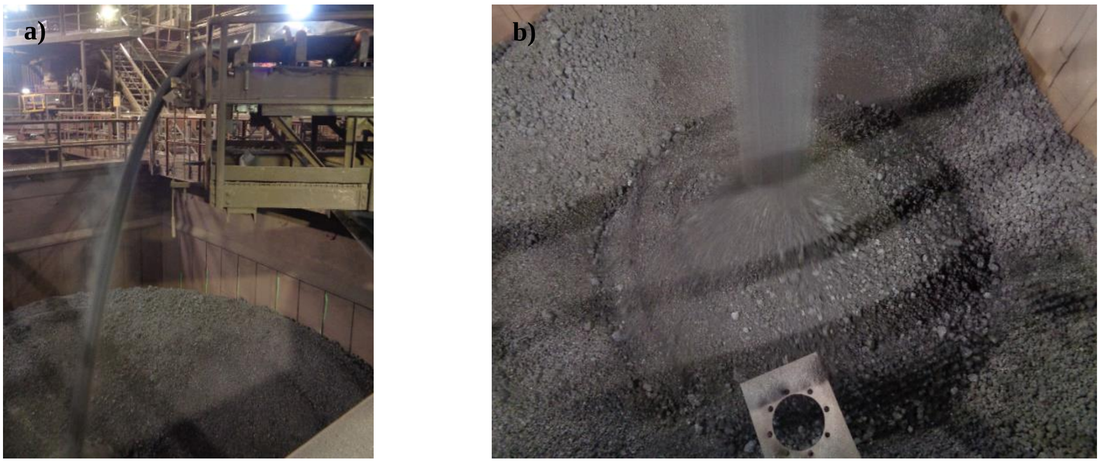

Figure 1 a) Sinter Bunker Filled by Conveyor Belt [5] **b)** Coarse Material at Outer Zones of the Pile

The current state was simulated by means of DEM with EDEM (Figure 2). Parameters for simulations were determined in angle of repose and slip tests in [9], rebound tests in [10] and further investigations regarding contact processes in [11]. In the simulations the bunker was filled with 350t with the original particle size distribution listed in Table 1. The small fractions 6, 10, and 16mm were combined in the simulation (52.25% in total), and all particles were up-scaled by factor 3 for computational efficiency.

At a filling level of 350t, the bunker was discharged and the particle size distribution at the outflow was determined in the simulation. In Figure 3a the mass fraction for each particle size in connection to the bunker filling level is shown. Small particles (6 + 10 + 16mm) contribute with approximately 80% to the total mass flow at the beginning and decrease to around 10% at the end of the discharging process. As shown in Table 1, the optimum would be a constant flow of 52.25% for the small particles during the whole discharging process. In contrast to this, the mass fraction of large particles is relatively small at the beginning of the discharging process and starts to increase at approximately 50% of the filling level. This effect can be explained by the core flow effect, whereby a core flow forms during discharging. This leads to an early discharge of material in the inner zones of the bunker, which are the smaller particles. The larger particles are accumulated at the outer zones (Figure 1).

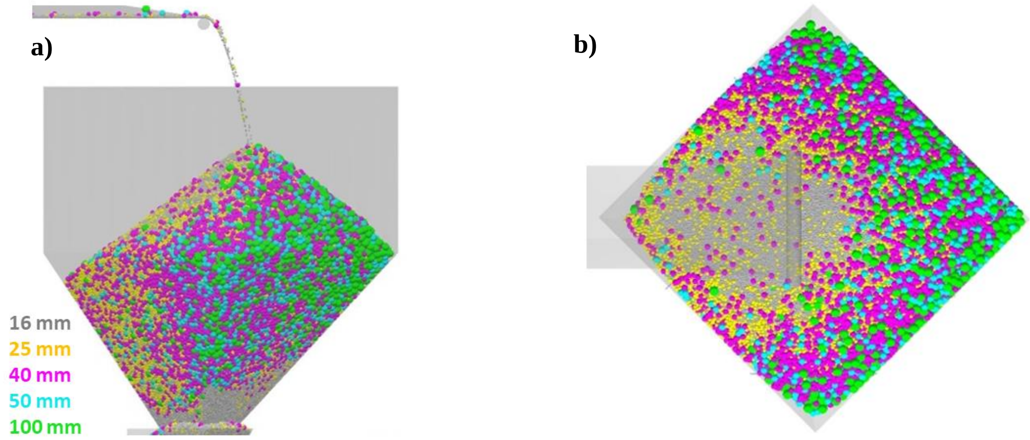

Figure 2 DE Simulation of the Bunker at Current State a) Side view b) Top view [12]

Table 1 Particle Size Distribution for Bunker Filling

Passing [mm]	Mass fraction [%]
100	9.39
50	6.40
40	17.03
25	14.93
16	17.56
10	22.04
6	12.65

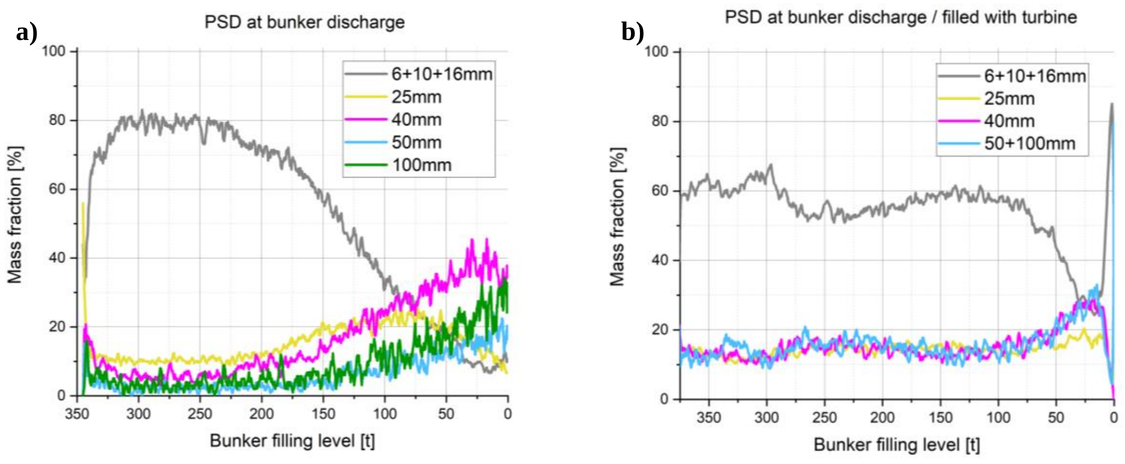

Figure 3 Particle Size Distribution at Bunker Discharge a) At Current State b) Filled with Turbine [5]

4. MEASURES TO REDUCE SEGREGATION EFFECTS

As the core flow effect is one of the main reasons for fluctuations in the particle size distribution during bunker discharge, the simplest measure to reduce these is to minimize the wall friction between the bunker and the bulk material. A friction coefficient of μ=0.89 between the steel wall and sinter was measured in experiments [9]. Simulations were repeated with a fictively reduced friction coefficient of μ=0.4 which significantly reduced segregation effects [5]. However, such a low friction coefficient is fictitious at the time of writing as a material interacting with sinter with a friction coefficient of μ= 0.4 and sufficient wear resistance is hardly provided with the current state of technology.

Another simple approach to reduce segregation effects would be a smart filling and discharging procedure. When the bunker is not completely discharged but filled again when a filling level of 50% is reached, also a more constant particle size distribution during the discharge is noticed in simulations. Due to the core flow effect, the material near the walls will never be discharged, which would lead to undesired material aging near the walls.

Various types of installations to reduce segregation effects during bunker filling were tested in simulations including cascade chutes and various types of solid state material driven turbines at different rotation speeds. The discharge from a conveyor belt was simulated with and without these installations. To determine segregation, the top view of the bulk material pile with only one particle size faded in was evaluated, see [5] for details. A significant improvement in terms of segregation was noticed with a pitchback turbine at low rotation speeds. The disadvantage is that a pitchback turbine needs a guide plate, which is an additional part exposed to wear. Good results were also noticed with an overshot turbine at low rotation speeds in this case, but this significantly worsened when tested with the given bunker geometry. The best results regarding the reduction of segregation effects were achieved with a cross flow turbine at low rotation speeds.

5. CROSS FLOW TURBINE

Compared to other simulated devices and types of solid state material turbines, the best results regarding a reduction of segregation effects were obtained with the cross flow turbine, shown in Figure 4. The cross flow turbine consists of 10 segmented blades, which form an ideal curvature for material flow. In this case the turbine diameter is 1.6m. The center of the cross flow turbine is hollow, which allows the material to flow through the turbine. The material flow through the turbine is shown in Figure 9a, which was simulated with the particle size distribution listed in Table 1. The color scale represents the translational velocity of the sinter particles. Simulations with different rotation speeds were performed and an optimum in terms of segregation was found at 5rpm. Depending on the mass flow, this low rotation speed can be achieved by regenerative braking or by an electric drive at low mass flows. The bunker filling process was simulated again with the cross flow turbine (Figure 5). The distance between conveyor belt discharge and turbine center was 2.556m. The 100mm particles were represented by 50mm particles, otherwise they would not pass the turbine due to the upscaling by a factor of 3. A significant reduction of segregation effects is noticed at bunker discharge when the bunker is filled with the cross flow turbine (Figure 3b). An almost constant particle size distribution till a filling level of 100t is noticed, which is a great improvement compared to Figure 3a. The cross flow turbine is developed and optimized to reduce segregation effects. Energy recovery is a secondary application. Other types of solid state material turbines [2–4] are optimized for energy recovery to achieve a higher power output.

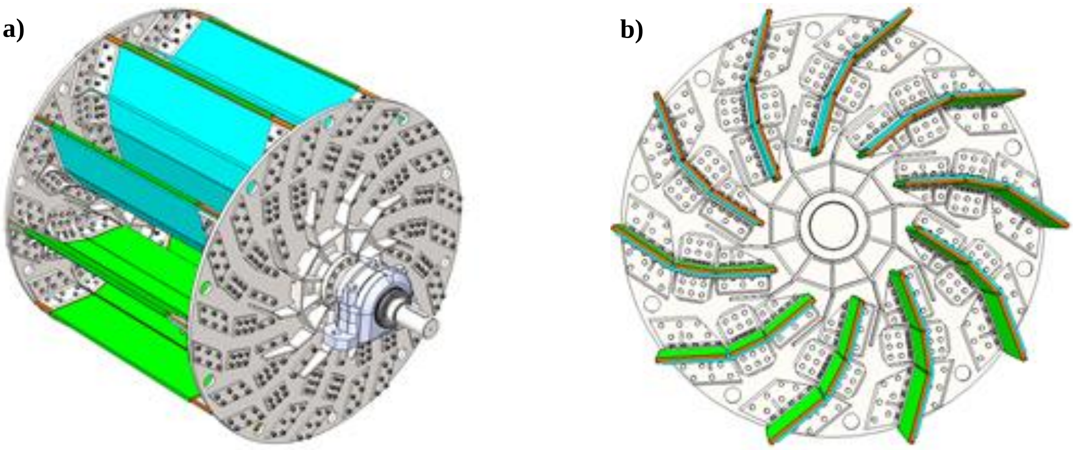

Figure 4 CAD Model of the Cross Flow Turbine (diameter 1.6m) [5]

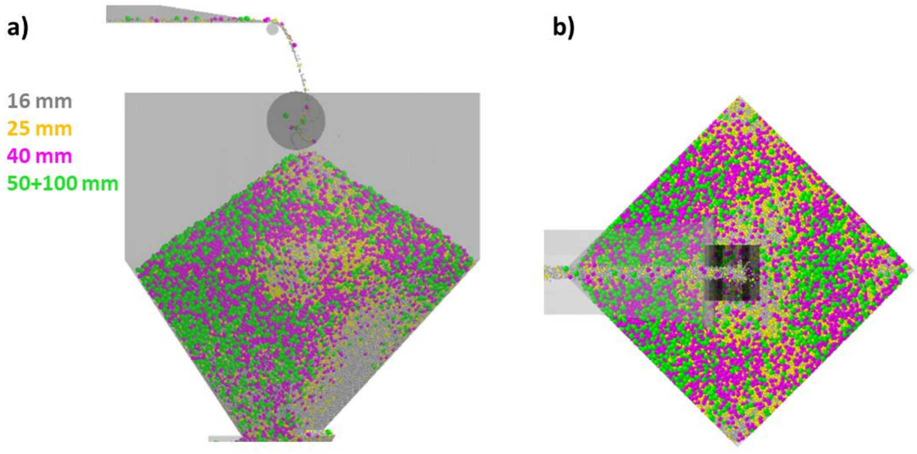

Figure 5 DE Simulation of Bunker Filled with Cross Flow Turbine a) Side view b) Top view [6]

6. MATERIAL DEGRADATION

The cross flow turbine significantly reduces segregation effects, but could eventually also cause damaging effects on particles. As a minimum grain size of 6.3mm is required for blast furnace operation, fines generation is especially critical for blast furnace sinter and is one main focus in conveying and storage processes, apart from equipment wear [12]. According to [13], 6% of the total mass flow of sinter provided at the blast furnace are fines due to conveying and storage processes in EU average. These fines have to be screened out before reaching the blast furnace and have to be re-sintered (return fines), which is quite an energy consuming process causing high emissions and costs [12].

On the one hand, the cross flow turbine splits and reduces free fall height by its diameter, but on the other hand, it causes additional impacts against the turbine and among the particles. To quantify the material degradation and fines generation caused by the turbine, a detailed investigation was necessary. Therefore, a recently developed breakage model for DEM was used [6, 14–16]. The novel breakage model is based on a probabilistic particle replacement with voronoi tessellated fragments. Depending on the stress on the individual particle, the initial particle is probabilistically replaced by different breakage patterns (Figure 6). Depending on the resulting fragment sizes, the breakage pattern is generated by means of the voronoi algorithm [17–19] with a certain amount of seeds. In contrast to [20] and other particle replacement models [21–25], where the particle is replaced by a number of spheres, in this model the initial particle is replaced by an exact copy of the initial particle, which has been previously tessellated. This ensures a mass and volume consistency. Polyhedral particles of any shape can be used. As the model is based on probabilities, a high amount of particles is necessary, but then the model delivers high accuracy in terms of fragment size distribution. Further breakage of fragments can also be simulated, which allows simulation of long and complex conveying systems with multiple breakage (Figure 8). How often a particle and its resulting fragments can be further broken is described with the breakage level L in Figure 8. For example, a breakage level of L = 2 means that the initial particle for this breakage process is a fragment of a previous breakage process at L = 1. The breakage model was programmed in C++ using an API (Application Programming Interface) in the simulation software ThreeParticle from Becker3D. A detailed description of the concept is provided in [6, 14]. The probability for each breakage pattern is dependent on the mechanical stress and is determined by single particle impact tests in [26–28]. The impact tests were performed with a specially developed automated single particle impact tester (Figure 7), which is described in detail in [26] and allows rapid analysis of breakage behavior of bulk materials. The model was verified and validated with a trial of shatter tests and trials with two different transfer systems in [6, 14] using different batches of sinter from two different manufacturers.

To quantify particle breakage caused by the cross flow turbine, a comparison of the drop with and without the turbine was performed in ThreeParticle (Figure 9). For computational efficiency, the simulation was simplified in order to simulate fewer particles in the bunker. To simulate the drop without the turbine, only the pile peak was simulated as a drop into a bulk material bed has a damping effect. The bulk material bed was placed at the same height as the bottom of the turbine, which would allow a direct comparison. The turbine reduced the drop height for the discharged material from h=3.356m to h_T=1.756m but caused additional impacts with the turbine and within the material. For evaluation a fragment collecting box was implemented, otherwise, the resulting fragments would have been deleted outside the simulation domain. Very soft material properties were assigned to the collecting box so that no breakage would occur due to impacts on the collecting box. A time step of $5x10^{-6}$ and the Hooke contact model were used. A detailed description of this simulation and parameters are described in [6].

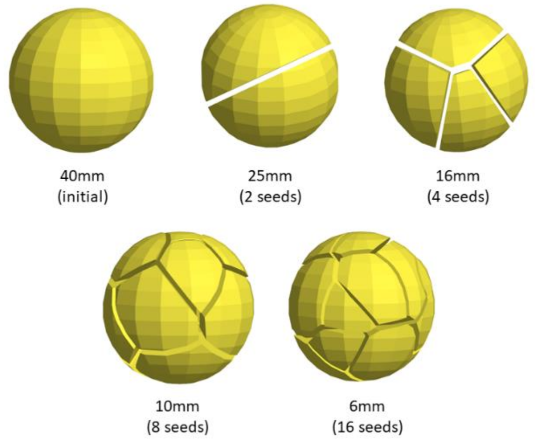

Figure 6 Breakage Patterns generated from a Voronoi Tessellated Polyhedral Particle [14]

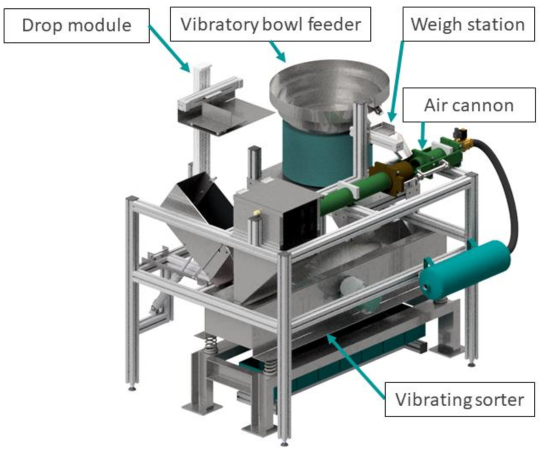

Figure 7 Automated single particle impact tester [26]

For comparison of particle damaging effects caused by the turbine, the same process was simulated with the cross flow turbine at different rotational speeds of 5, 10, 20, 30, 40 and 50 rpm. 5 rpm is the optimum for reducing segregation effects and 30-40 rpm for energy recovery. Simulations in [6] show that at 5 rpm the material flows through the turbine, which results in a mixing effect and reduces segregation. This is not the case at 30 rpm, where the material remains on the same turbine blade and causes a higher torque on the turbine. The material forms a bulk material bed inside the turbine, which is assumed to have a significant damping effect. As the damping effect depends on the PSD in the material bed and smaller particles lead to higher damping, the small particles were also simulated in this case. The PSD for the simulation equaled the original PSD from the bulk sample of the sinter plant (Table 1). It has to be stated that only the size fractions 10-16, 16-25 and 25-40 mm were breakable in this case, which were represented by polyhedral particles of spherical shape with diameters of 16, 25 and 40 mm in the simulation. No experimental data for the fractions 6-10, 40-50 and 50-100 mm are available. The fines and the non-breakable particles were represented by spheres with a diameter of 6, 10, 50 and 100 mm in the simulations. A total mass of 122.9 kg sinter was simulated, which was equivalent to 160512 particles with this PSD.

The results of the particle breakage evaluation for 5 rpm (reduce segregation effects) and 30 rpm (energy recovery) are shown in Figure 10, which shows the increase in mass fractions for each particle size due to the bunker filling process. The diagram does not include the size fractions 40-50 and 50-100 mm as 50 and 100 mm particles were not breakable in this simulation. More breakage occurs at the drop with the cross flow turbine at 5 rpm and about 1% more fines are produced in this case, compared to the case without turbine. It is assumed that volume breakage occurs mainly due to impacts on the blade edges, where also the most wear occurs, and generation of fines is mainly due to abrasion among sinter particles inside the turbine. Significantly less particle breakage occurs if the turbine is operated with a higher rotation speed of 30 rpm for energy recovery. 0.5% less fines are produced at 30rpm compared to the case without turbine. It was assumed that the turbine has an even more particle-preserving effect at higher rotation speeds, but is limited to a certain rotation speed as the particle preserving effect of a damping material bed on the blades also decreases with higher rotation speeds. For this purpose, the fines production in dependence on the rotation speed was investigated for this case (Figure 13). A minimum for the fines production is noticed at 30 rpm, which confirms the assumption.

Various studies confirm that replacing a drop by several smaller drops leads to less particle breakage [29]. Thus, material degradation is not only dependent on the rotation speed, but also on the mounting height of the turbine and bunker filling levels. The reduction of particle breakage due to splitting the drop height into two smaller drops could not be evaluated with the simulations described in this work. Overall, it is assumed that the turbine leads to less particle breakage during a whole bunker filling process, but this needs to be confirmed by further investigations.

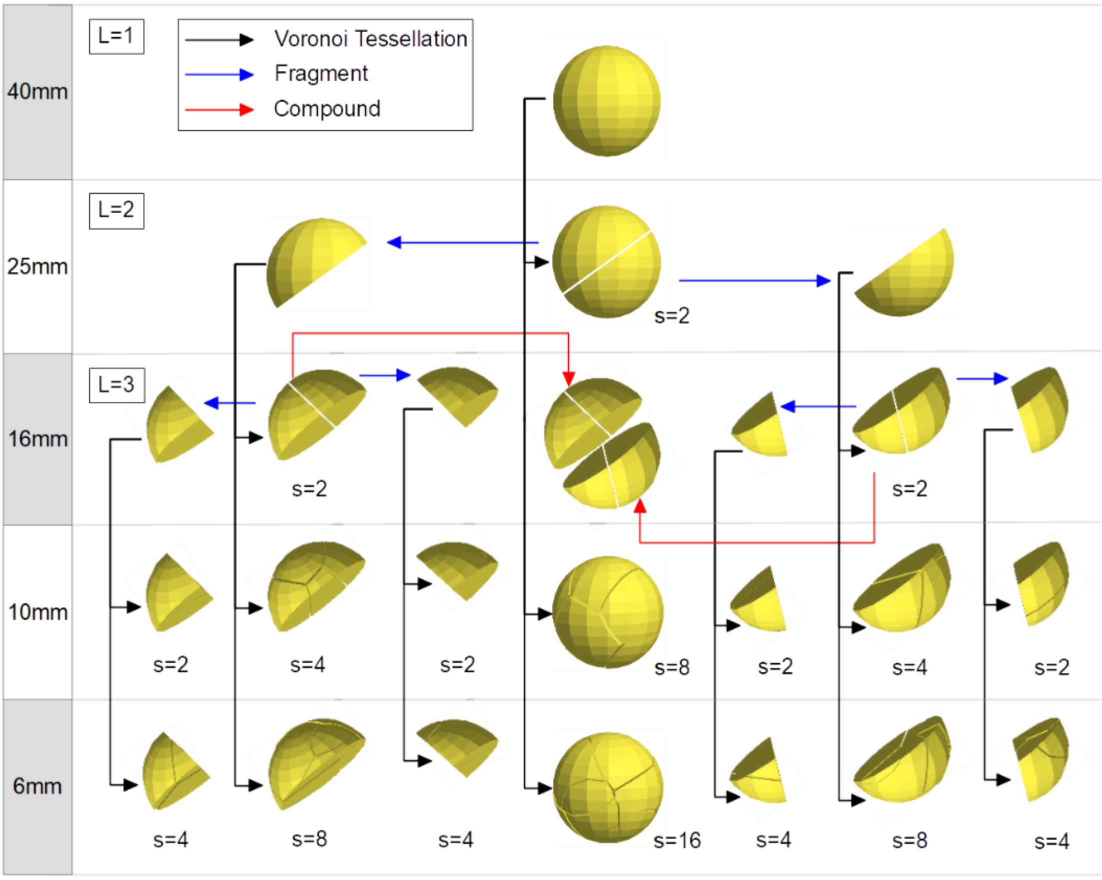

Figure 8 Multiple Breakage on 3 Breakage Levels (L=1...3) with Splitting in 2 Fragments (s=2) [6]

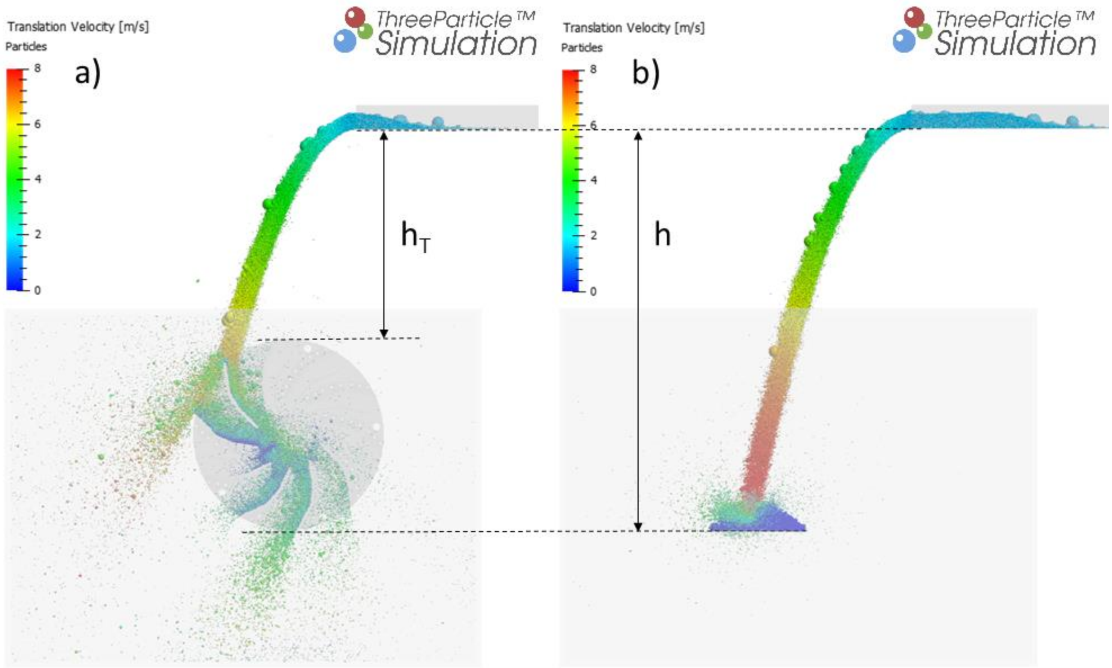

Figure 9 Breakage Simulation of Bunker Filling with the Novel Breakage Model a) With Cross Flow Turbine at 5rpm (h_T=1.756m) b) Without Turbine (h=3.356m) [5]

7. WEAR

As sinter is a very abrasive material, wear investigations were conducted. Experiments at a sinter plant with 300t/h mass flow and conveyor belt speeds of 1.43m/s were performed. The wear resistant material Hardox 600 was used. A plate (300x300mm) of 15mm thickness was worn out (first through holes) after 23114t of sinter collided the plate. This experiment was simulated by means of DEM with EDEM. A triangular mesh of 10mm was used and the sum of the tangential and normal cumulative contact energy after 50s of operation was determined. This data and simulation results of the cross turbine at different rotation speeds were used to calculate the expected wear resistance of the cross flow turbine in operation at the same conditions. Calculations revealed that 102980t sinter at 5rpm or 174791t sinter at 35rpm can be handled by the cross flow turbine until a 15mm surface erosion, if equipped with Hardox 600. The wear maxima were noticed at the blade edges [5]. As worn blade edges do not lead to operating failure of the turbine, the actual lifetime of the turbine is much higher.

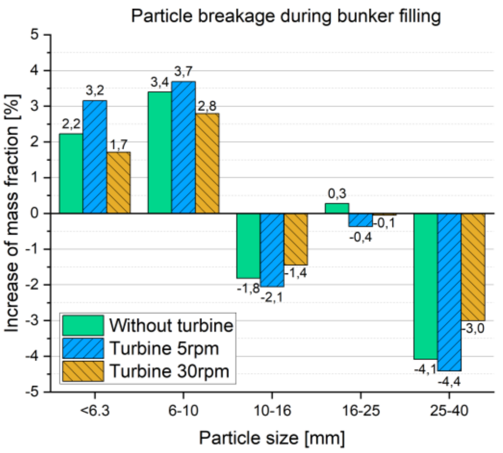

Figure 10 Particle Breakage During Bunker Filling without and with the Cross Flow Turbine at 5rpm (reduce segregation) and 30rpm (energy recovery) [6]

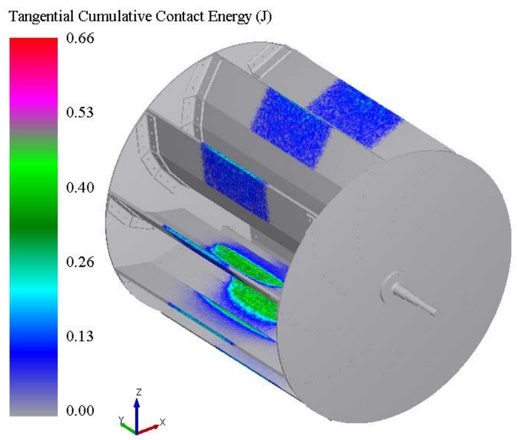

Figure 11 Wear Evaluation on Cross Flow Turbine with Cumulative Contact Energy [J] at 35rpm

8. POWER OUTPUT

Additionally, the torque was evaluated for different rotation speeds (Figure 12). The drop height measured from belt conveyor discharge to turbine bottom is 3.356m (turbine diameter 1.6m). Conveyor belt speed is 1.43m/s. Analysis of simulations shows large scattering and peaks due to impacts of differently sized particles. The torque data has been smoothed using the LOWESS method (Locally Weighted Scatterplot Smoothing) in the visualization software Origin. From the smoothed torque curves, the average torque for each rotation speed was determined and the average power output was calculated, which are both shown in Figure 13. The highest power output is noticed at 35rpm, which confirms previous investigations with EDEM regarding the optimum rotation speed for energy recovery in [5, 7]. The calculated theoretical power output considering potential and kinetic energies is 2829W for this case with 300t/h. Thus, the efficiency of the turbine is η=39.5% at 35rpm. Figure 13 also shows that the maximum power output is at a similar rotation speed as the minimum of fines generation. It is assumed that a high energy transfer from the bulk material to the turbine leads to a reduction of energy available for particle breakage.

9. CONCLUSIONS

The cross flow turbine presented in this work significantly reduces segregation effects in storage processes. This was proven at the example of a bunker used for blast furnace sinter. A more evenly distributed particle size distribution at the bunker outflow is noticed. The optimum rotation speed to reduce segregation effects is 5rpm and is 35rpm for energy recovery. Fines generation due to the turbine was evaluated using a novel breakage model for DEM. At 5rpm slightly more fines are produced due to the turbine, but it is assumed that the reduction of drop height due to the turbine compensates this effect. At higher rotation speeds (30-40rpm) significantly less fines are produced due to the turbine. With this turbine a simple device to reduce segregation or for energy recovery is provided, which is easily installable in existing plants. The cross flow turbine is currently being built and a trial at a steel manufacturing plant is planned in the near future.

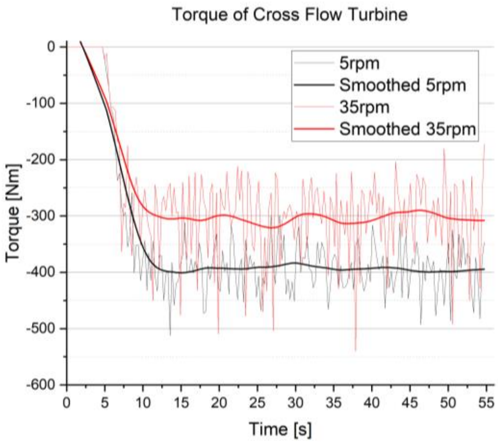

Figure 12 Evaluation of the Torque on the Cross Flow Turbine at Different Rotational Speeds with 300t/h Sinter and a Drop Height of 3.356m (Belt Discharge to Turbine Bottom)

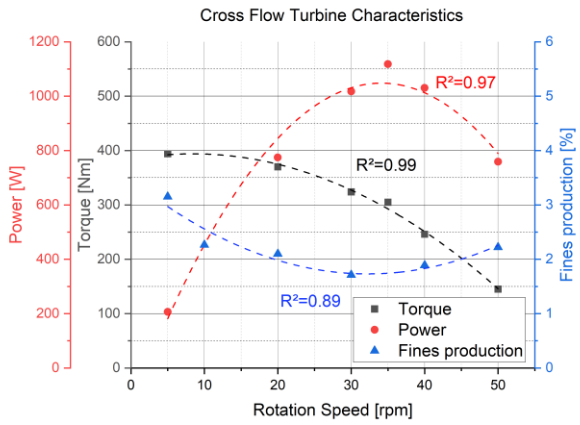

Figure 13 Fines Production, Torque and Power Output of the Cross Flow Turbine at Different Rotational Speeds for 300t/h Sinter

10. ACKNOWLEDGMENTS

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REFERENCES

[1] M. Prenner (2012) Solid state material driven turbine: International Patent F03G3/02 F03G3/04
[2] M. Prenner (2015) Feststoffturbine zur Energierückgewinnung in Kombination mit Gurtförderanlagen. Berg Huettenmaenn Monatsh 160:21–31. https://doi.org/10.1007/s00501-014-0327-0
[3] M. Prenner, C. Grübler, S. Zeiler (2018) Vorteile von Feststoffturbinen. Schüttgut:68–72
[4] M. Prenner (2019) Energy Recovering System for Moving Bulk Materials. EARTH 8:20. https://doi.org/10.11648/j.earth.20190801.13
[5] M. Denzel, M. Prenner, N.A Sifferlinger (2023) Solid State Material Driven Turbine to Reduce Segregation during Bunker Filling. Berg Huettenmaenn Monatsh. https://doi.org/10.1007/s00501-022-01311-6
[6] M. Denzel (2023) A Breakage Model for Discrete Element Simulations Applied to Iron Ore Sinter. PhD Thesis, University of Leoben. https://doi.org/10.34901/mul.pub.2023.01
[7] M. Denzel, M. Prenner (2022) Solid State Material Driven Turbine to Reduce Segregation Effects in Bunkers. In: CHoPS 2022 - 10th International Conference on Conveying and Handling of Particulate Solids, Salerno, Italy
[8] J. Nohl, B. Domnick (2000) Stockpile Segregation: Technical Paper T - 551. Superior Industries
[9] M. Prenner (2018) Simulationsparameterstudie - Sinterbunker (Simulation parameter study - Sinter bunkers). Project report, University of Leoben
[10] M. Brugger (2021) Rücksprungverhalten von Hochofensinter (Rebound behaviour of blast furnace sinter). Bachelor Thesis, University of Leoben
[11] P. Kogler (2020) Analyse von Kontaktvorgängen und Optimierung von fördertechnischen Anlagen hinsichtlich Partikelbruchs bei Sinter. Masterarbeit, Montanuniversität Leoben
[12] M. Denzel, M. Prenner (2021) Minimierung des Sinterzerfalls mittels DEM (Minimization of Sinter Degradation with DEM). Berg- und Huettenmaennische Monatshefte (BHM) 166:76–81. https://doi.org/10.1007/s00501-021-01081-7

[13] R. Remus, M.A Aguado-Monsonet, S. Roudier et al. (2013) Best available techniques (BAT) reference document for iron and steel production: Industrial emissions Directive 2010/75/EU : integrated pollution prevention and control. Scientific and technical research series, vol 25521. Publications Office of the European Union, Luxembourg

[14] M. Denzel, M. Prenner, N.A Sifferlinger (2022) A probabilistic particle replacement model to simulate bulk material degradation during conveying processes using DEM. Montanuniversität Leoben. Proceedings MHCL 2022 - 24th International Conference on Material Handling, Constructions and Logistics in Belgrad, Serbia:29–36. https://doi.org/10.34901/mul.pub.2023.02

[15] M. Denzel (2022) Partikelbruch in der Fördertechnik: Prüfmethodik und Simulation mittels Diskrete Elemente Methode. Bergbau - Zeitschrift für Rohstoffgewinnung, Energie, Umwelt 73:436–440. https://doi.org/10.34901/mul.pub.2023.03

[16] M. Denzel (2022) Partikelbruch in der Fördertechnik - Prüfmethodik und Simulation mittels Diskrete Elemente Methode (Particle breakage during conveying processes - Test method and simulation with the discrete element method). In: Langefeld O (ed) 10. Kolloquium - Fördertechnik im Bergbau, 1st edn. Papierflieger Verlag GmbH, Clausthal-Zellerfeld, pp 89–101

[17] S. Kumar, S.K Kurtz (1993) Properties of a two-dimensional Poisson-Voronoi tesselation: A Monte-Carlo study. Materials Characterization 31:55–68. https://doi.org/10.1016/1044-5803(93)90045-W

[18] S. Kumar, S.K Kurtz (1994) Simulation of material microstructure using a 3D voronoi tesselation: Calculation of effective thermal expansion coefficient of polycrystalline materials. Acta Metallurgica et Materialia 42:3917–3927. https://doi.org/10.1016/0956-7151(94)90170-8

[19] R. Riedinger, M. Habar, P. Oelhafen et al. (1988) About the Delaunay-Voronoi tesselation. Journal of Computational Physics 74:61–72. https://doi.org/10.1016/0021-9991(88)90068-X

[20] L.M Tavares, A.S das Chagas (2021) A stochastic particle replacement strategy for simulating breakage in DEM. Powder Technology 377:222–232. https://doi.org/10.1016/j.powtec.2020.08.091

[21] P. Cleary (2001) Modelling comminution devices using DEM. Int J Numer Anal Meth Geomech 25:83–105. https://doi.org/10.1002/1096-9853(200101)25:1<83:AID-NAG120>3.0.CO;2-K

[22] M. Sousani, A. Chagas, A. Saxena et al. (2019) Simulation of Surface Damage and Body Breakage by using DEM

[23] G.K Barrios, N. Jiménez-Herrera, L.M Tavares (2020) Simulation of particle bed breakage by slow compression and impact using a DEM particle replacement model. Advanced Powder Technology 31:2749–2758. https://doi.org/10.1016/j.apt.2020.05.011

[24] P.W Cleary, M.D Sinnott (2015) Simulation of particle flows and breakage in crushers using DEM: Part 1 – Compression crushers. Minerals Engineering 74:178–197. https://doi.org/10.1016/j.mineng.2014.10.021

[25] G.W Delaney, R.D Morrison, M.D Sinnott et al. (2015) DEM modelling of non-spherical particle breakage and flow in an industrial scale cone crusher. Minerals Engineering 74:112–122. https://doi.org/10.1016/j.mineng.2015.01.013

[26] M. Denzel, M. Prenner, N.A Sifferlinger (2022) Development of an automated single particle impact tester for iron ore sinter. Minerals Engineering 175:107291. https://doi.org/10.1016/j.mineng.2021.107291

[27] M. Denzel, M. Prenner (2022) Partikelbruchvorhersage an einem dynamischen Übergabesystem und Vergleich mit einer herkömmlichen Schurre mittels DEM (Particle breakage prediction on a dynamic transfer system and comparison with a conventional chute using DEM). Berg Huettenmaenn Monatsh 167:66–75. https://doi.org/10.1007/s00501-022-01197-4

[28] M. Denzel, M. Prenner (2021) Dynamisches Übergabesystem zur Reduktion des Partikelbruchs (Dynamic transfer system to reduce particle breakage). 25. Fachtagung Schüttgutfördertechnik 2021:233–242. https://doi.org/10.25673/36794

[29] R.K Sahoo (2007) Degradation characteristics of steel making materials during handling. Powder Technology 176:77–87. https://doi.org/10.1016/j.powtec.2007.02.013