Solid State Material Driven Turbine

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Abstract
Bulk materials which are transported with continuous conveyors, partly have a high energy content, depending on the specified mass flow and the conveying velocity. At discharge points to storage areas or at transfer points from one conveyor to another, the energy content often increases due to the elevation of the discharge conveyor. It is possible to recover a large part of the energy due to the mass flow (conveying velocity) and the drop height of the bulk material at these points. A so-called "Solid State Material Driven Turbine" has been developed at the "Chair of Mining Engineering and Mineral Economics - Conveying Technology and Design Methods" at the Montanuniversität Leoben / Austria , which allows recovery of this energy. This energy can be transferred directly to the conveying system or via a generator to the electric circuit. In addition to energy recovery, this technology offers further benefits, which could be even more interesting than the actual energy recovery. This paper introduces this new technology and focuses on additional benefits like wear reduction, avoiding particle size segregation, soft loading effects etc. Turbine prototypes, wear tests, simulation examples and economic considerations are shown.

1. Introduction
The use of belt conveyors for transportation of bulk materials is an efficient solution, especially for high mass flows. To increase the efficiency of such conveyors, energy recovery systems can be used. The standard operation for belt conveyors is regenerative braking during a downwards conveying process [1], [2]. For this process a contact between the bulk material and the conveyor and a vertical height between the feeding and the discharge station is necessary. An alternative energy recovery method has been developed at the "Chair of Mining Engineering and Mineral Economics - Conveying Technology and Design Methods" at the Montanuniversität Leoben/ Austria. A so-called "Solid State Material Driven Turbine" [3], whose functional principal is similar to a simple hydrogen turbine respectively to a water wheel, can be used to recover energy from free flowing bulk materials at feeding, discharge or transfer points. The recoverable energy depends on the mass flow, the conveying speed and the usable drop height. In order to illustrate the potential of such an energy recovering system, a simple calculation can be carried out. For example a mass flow of 15 000t/h (4166.7kg/s) at a conveying velocity of 6m/s with a drop height of 2m leads to a power content of about 157kW, which is inherent to the moving bulk material. Usually a large part of this energy or power will be converted into "wear" of the conveying system or the bulk material at feeding, discharge or transfer points. This unused energy is available free of charge and could be better used to achieve more environmentally friendly continuous conveying systems.

In addition to energy recovery, this technology offers further benefits, which could be even more interesting than the actual energy recovery. Simulations showed that the wear of a turbine, if it is used instead of a standard transfer chute between belt conveyors, is much lower than the wear of a standard transfer chute. Also soft loading effects for belt conveyors could be realized using a special turbine geometry. Particle segregation and degradation during conveying, storage, discharge and transfer processes can be a problem for downstream facilities like blast furnaces or crushers. This problem could also be reduced by using a "Solid State Material Driven Turbine". The following chapters will give an introduction to this topic.

2. Theory of Operation

The operation theory of a "Solid State Material Driven Turbine" is similar to a simple hydraulic turbine. Due to the simple construction, the principles of water wheels (overshot, undershot, breastshot or pitch back - Figure 1 [4]), cross flow turbines (Ossberger turbine - Figure 1 [5]) or horizontally mounted water wheels ("Stoßrad" - Figure 1 [6]) could be adapted for energy recovery from moving bulk materials. The main difference between a water turbine and a "Solid State Material Driven Turbine" is the wear behaviour. Bulk materials induce significantly more wear to the turbine than water. It is essential to line the turbine blades with wear plates to realize a adequate service life. These necessary wear plates are difficult to machine and have to be replaced frequently. The geometry of the turbine blades should be constructed as simple as possible to reduce the operational costs. A simple construction with highest possible efficiency decreases the payback period.

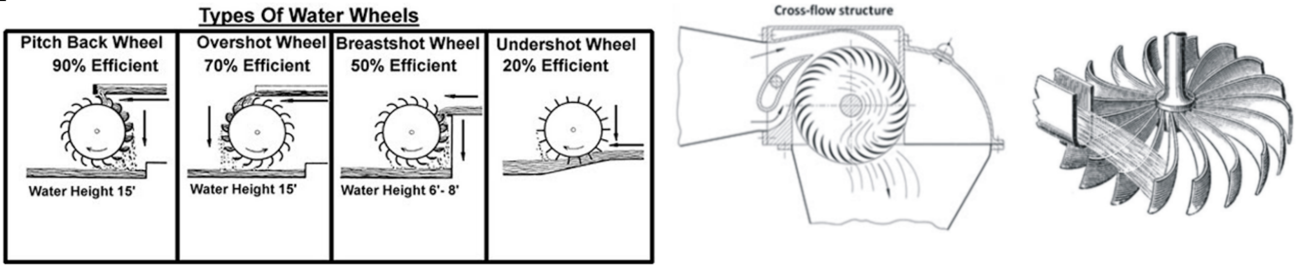
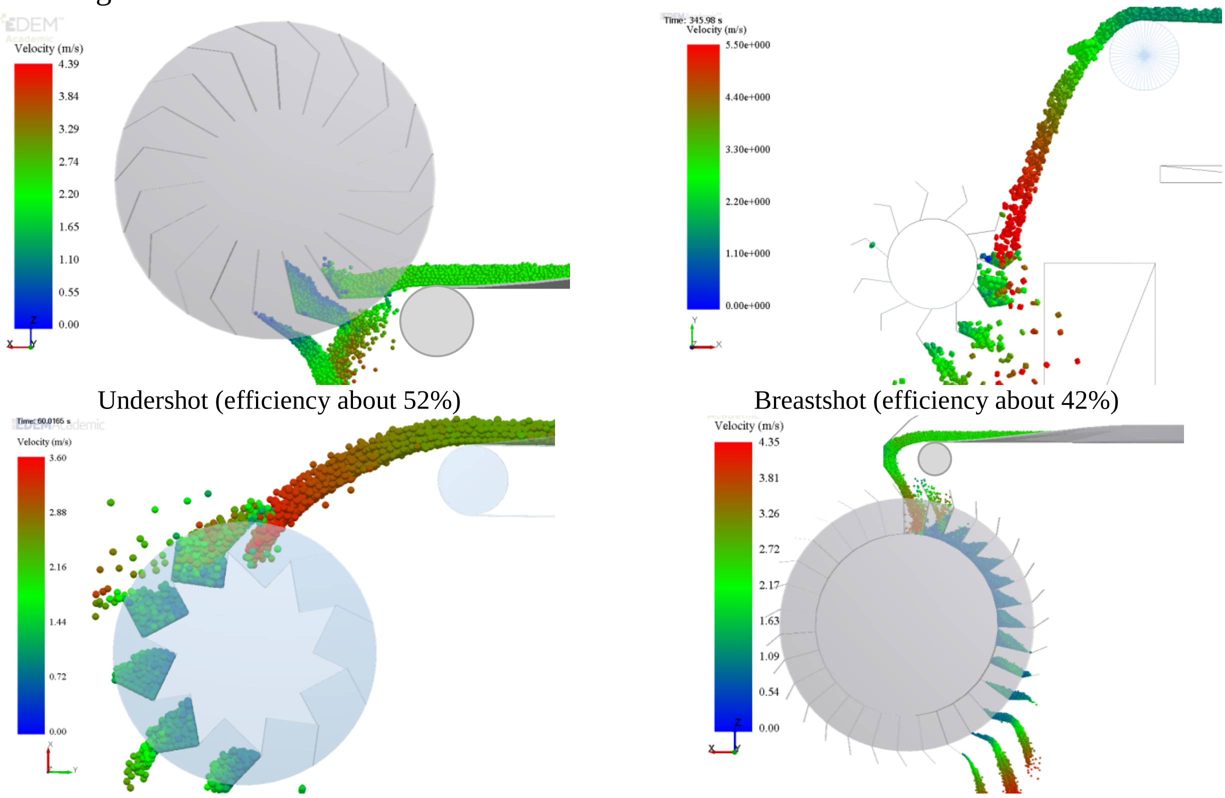


Figure 1: Types of water wheels[4], Crossflow turbine - "Ossberger turbine" [5], horizontally mounted water wheel - "Stoßrad" [6]

The "Discrete Element Method" (DEM) is an established tool to design and calculate the expected power output of a "Solid State Material Driven Turbine". Figure 2 shows simulation examples of the early stage development of undershot, breastshot, overshot and pitch back turbines. The efficiency (see next paragraph) of the different turbine types, calculated with the DEM, can also be seen in Figure 2.



Undershot (efficiency about 52%)

Breastshot (efficiency about 42%)

Overshot (efficiency about 50%)

Pitch back (efficiency about 70%)

Figure 2: DEM simulations of different turbine types

Figure 3 depicts a possible application for "Solid State Material Driven Turbines". A turbine could be implemented at three different positions at this transfer station. The figure shows the different power contents in these positions. The content is calculated using the sum of the kinetic and the potential energy. The vertical height, used for calculating the potential energy, is always between the discharge point of the bulk material at the conveyor belt and the lowest point of the turbine. The power content will be used to calculate the efficiency. At position three the power content is 217kW. Using an efficiency of about 50%, which is a realistic value, 110kW can be used for energy recovery.

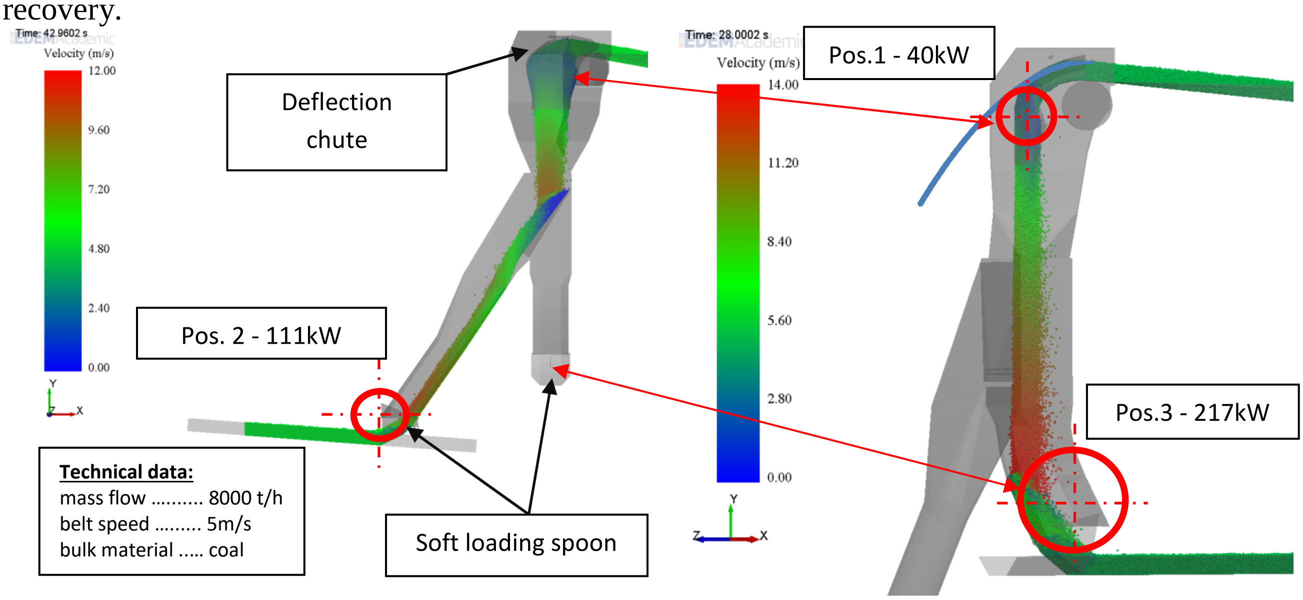


Figure 3: Possible field of application for "Solid State Material Driven Turbines"

3. Turbine prototypes tested under operational and laboratory conditions

To confirm the feasibility of a "Solid State Material Driven Turbine", two turbines were designed and built at the "Chair of Mining Engineering and Mineral Economics - Conveying Technology and Design Methods" (see Figure 4).

3.1. Turbine for laboratory tests

The first turbine was built for laboratory tests (Figure 4 left [7]) to verify the "Discrete Element Simulation" (DE simulation) results. Simulations and test results showed a very good correlation. With a mass flow of 28.13kg/s, a belt speed of 2.5m/s, a vertical height of 993mm and a turbine diameter of 765mm, 163W of power could be recovered in the simulation. The power output of the turbine in the laboratory test under same conditions was 152W. The difference of about 7% can be interpreted as losses due to the used bearings, chain drive and electric motor. With the used simulation programme (EDEM from the company DEM Solutions Ltd.), it was not possible to consider these losses. The recovered energy (respectively power) was directly transferred to the drive pulley by the use of a chain drive. The power consumption of the five meter long discharge conveyor was about 928W and could be reduced by about 16% using this turbine. An efficiency of 42% could be calculated.

3.2. "Solid State Material Driven Turbine" under realistic operating conditions

To get more information about the behavior of a "Solid State Material Driven Turbine" under realistic operating conditions, it was decided to implement a turbine at a transfer point between a belt conveyor and a crusher (Figure 4 right). The conveyed bulk material was lime stone. The test was carried out over two months. The turbine was demounted after this period, because a belt conveyor with higher capacity had to be installed. In this case a good correlation between the simulations and the measurements could also be documented. The specified maximum mass flow at the used discharge conveyor belt was 400t/h at a belt speed of 1.6m/s. The grain size distribution for the conveyed lime stone was specified between 10m% smaller than 4mm and 10m% bigger than 70mm with a maximum of 300mm. The vertical height was about 2.5m. The simulation result for the power output was 1193W. This value could not be reached under operating conditions, because there was a major difference between the specified and the real particle size distribution. The particles bigger than 70mm were almost 50% and the maximum particle size was also much bigger than 300mm. For that reason, the power output was only 850W. This value could be confirmed by simulation after using the actual particle size distribution. This higher amount of bigger particles and the greater maximum particle size caused a much higher impact force at the turbine blades, which was not considered during the design phase. For this reason fractures of weld seams occurred, however no function-relevant parts of the turbine were affected. Furthermore the bolting of the turbine blades lost its pre-load, whereby the threaded holes were deformed. So the bolts had to be tightened once a week. All other components of the turbine operated without any problems. Also the expected clogging challenges due to the cohesive fine grained limestone particles were not relevant. In order to handle the real particle size distribution, only a few improvements have to be made. The size of the turbine blades and thereby the turbine diameter has to be increased. Also the turbine blades may need to be strapped, in order to support each other. With a bigger breastshot turbine an efficiency of about 45% can be realized.

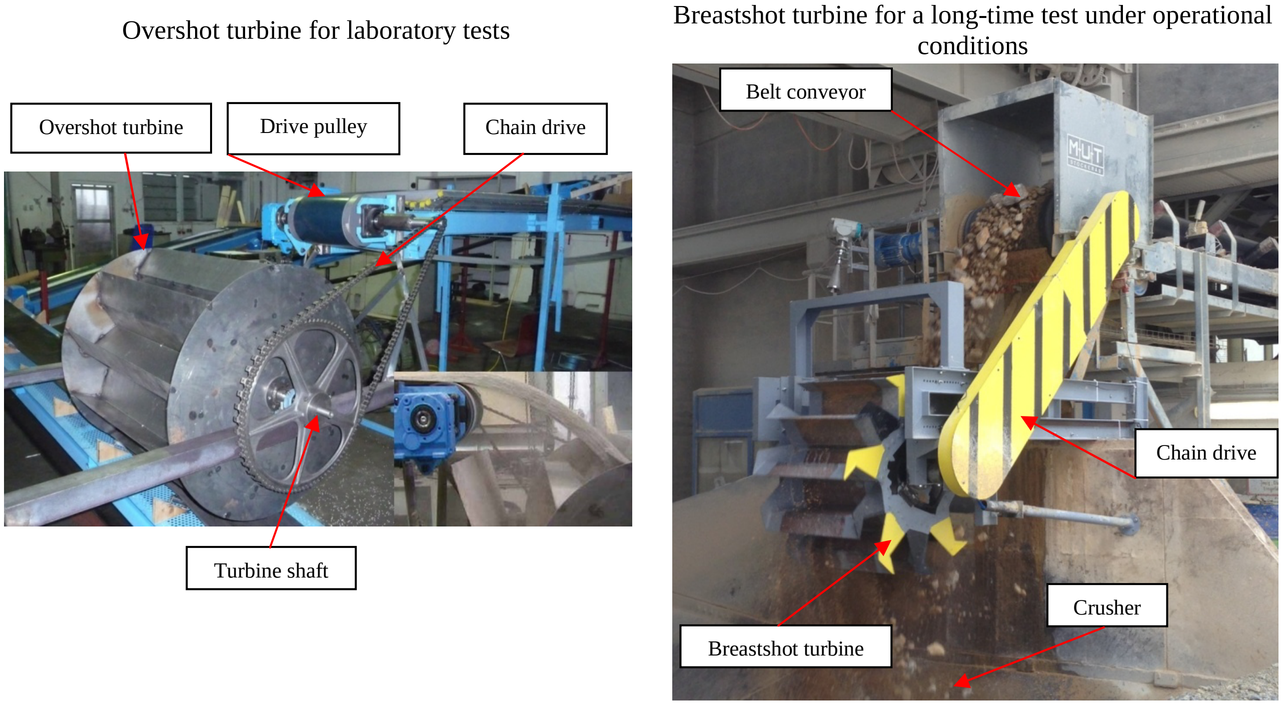


Figure 4: Turbine prototypes

4. Additional benefits of "Solid State Material Driven Turbines"

The primary application of a "Solid State Material Driven Turbine" is the recovery of energy from moving bulk materials. During various tests, which were carried out in the past, several additional benefits could be found. These additional benefits could be even more interesting and might also have a higher economic impact than the actual energy recovery. In this chapter four additional benefits are presented. A major benefit is a significant wear reduction compared to standard transfer chutes which could be replaced by turbines. Furthermore, by using a turbine, particle size segregation and particle breakage can be avoided or reduced. With a special turbine type a soft loading effect at transfer points from one conveyor to another can be realized.

4.1. Wear benefit and soft loading effect

During a project which was funded by the European Union (*The research leading to these results has received funding from the European Union's Research Fund for Coal and Steel (RFCS) research programme under grant agreement number <RFSR-CT-2015-00027>.*), long-time wear tests with different chute types were carried out. This chutes were all implemented at the same transfer station between two belt conveyors (mass flow 800t/h, belt speed 2.4m/s, transfer height about 3m, cf. Figure 5), which are used for conveying iron ore and were lined with different wear plates to improve durability. One of the wear plate materials was HARDOX 400, which was used as reference material. HARDOX 400 should normally not be used for wear protection at highly stressed chute areas in combination with iron ore, because iron ore is a highly abrasive bulk material. Since HARDOX is a low-cost wear protection material its application limits should be determined. To describe the wear benefits of "Solid State Material Driven Turbines" the wear test results of HARDOX 400 were used. Figure 6 to Figure 9 show the test and simulation results for HARDOX 400 for the tested chutes. The test results were compared with DE simulations. For all simulations, the same geometry grid size and the same simulation parameters were used. The wear tests were stopped after 10mm of HARDOX was removed from the chute surface. The "Archard Wear" [8] and the cumulative contact energy (normal and tangential) were calculated by using the DEM. The contact energy simulation results in combination with the chute test results were used for live time prediction of different "Solid State Material Driven Turbines". The simulation values calculated by the "Archard Wear" model could not be used for live time prediction because they showed no correlation with the actual wear behaviour.

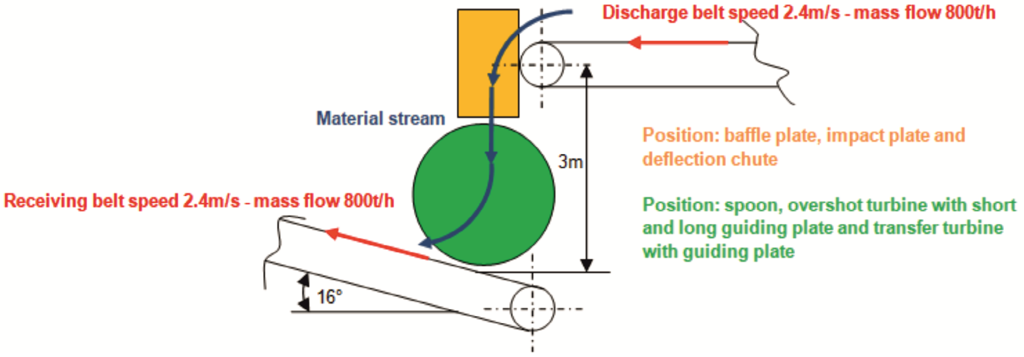


Figure 5: Transfer situation for all chute and turbine tests

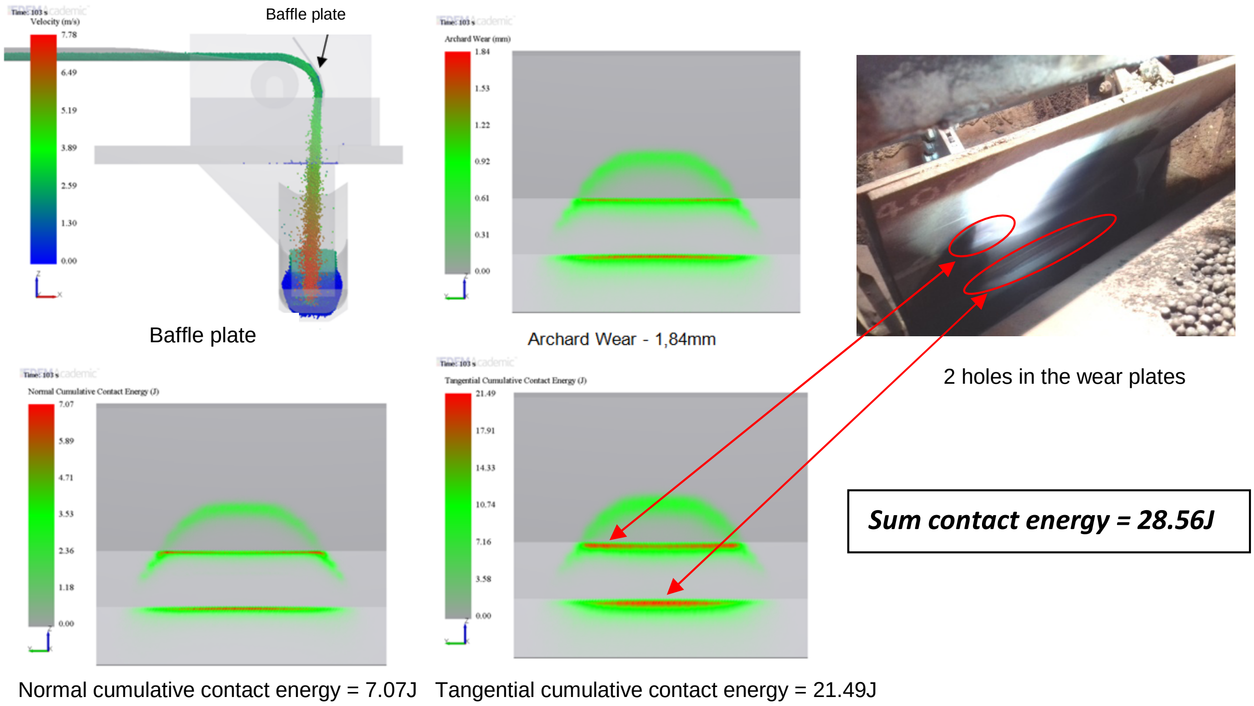


Figure 6: Test results and DE simulation - baffle plate

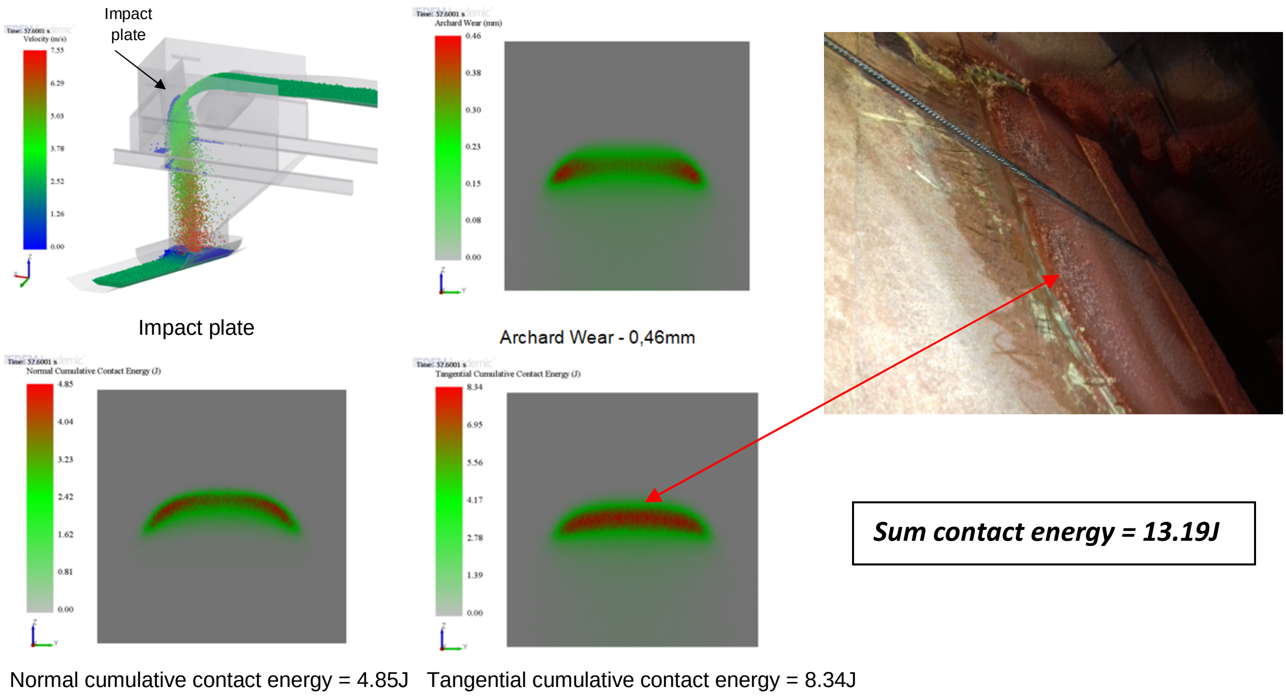


Figure 7: Test results and DE simulation - impact plate

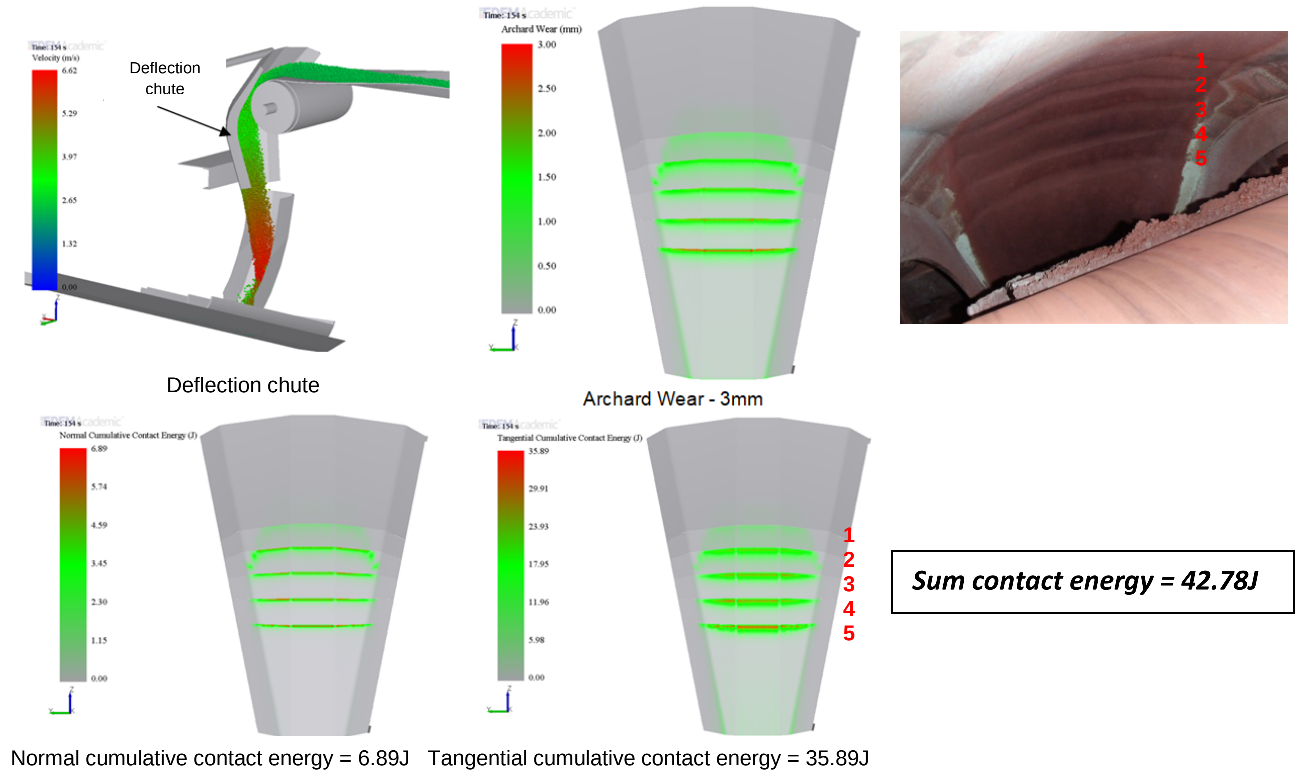


Figure 8: Test results and DE simulation - deflection chute

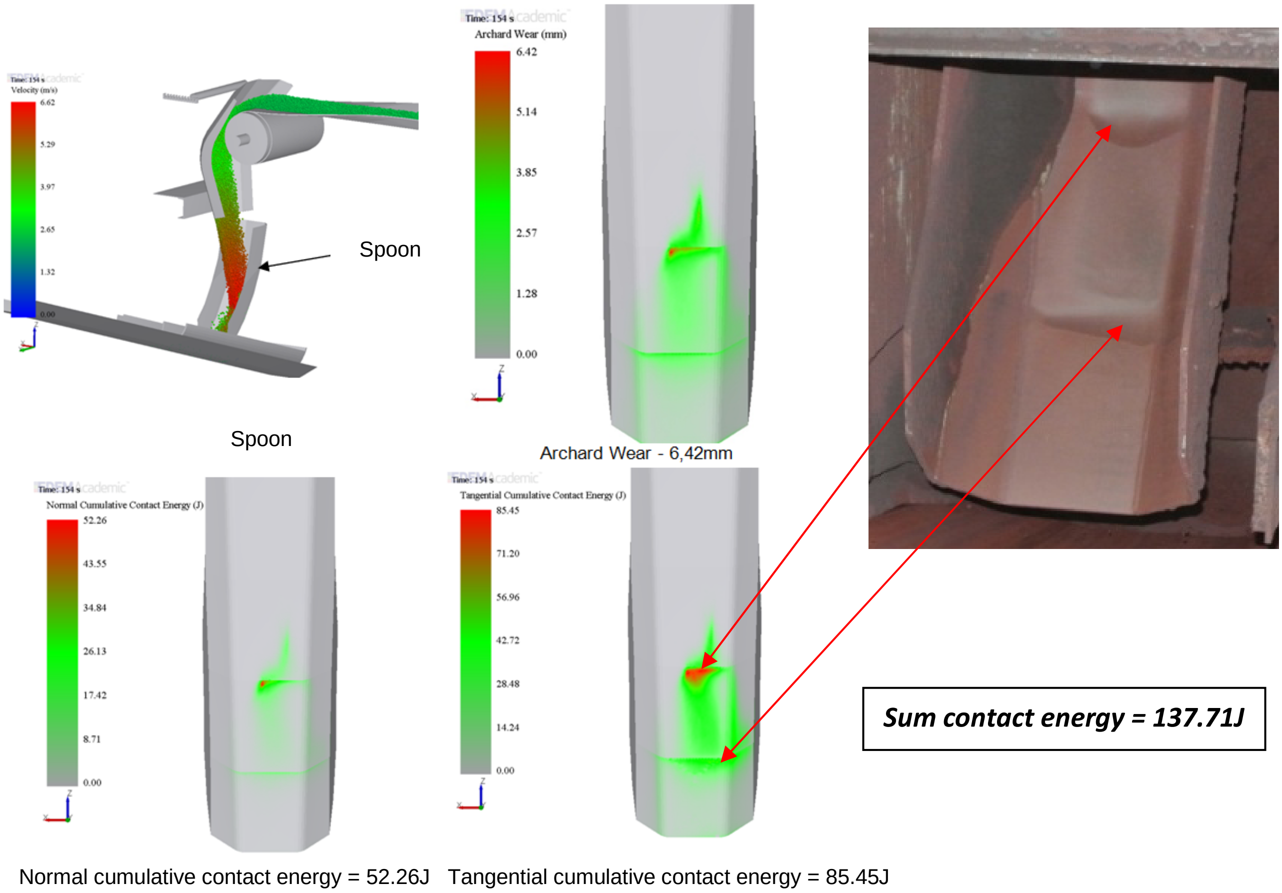


Figure 9: Test results and DE simulation - spoon

Due to organisational reasons, it was not possible to measure the exact time respectively the exact amount of iron ore, which came into contact with the different chutes. Only for the impact plate (Figure 7), which had a wall thickness of more than 10mm, it was possible to measure the flow rate of iron ore (186 439 tonnes) until 10mm of HARDOX was removed from the plate surface. All the other chutes with 10mm wall thickness got a hole between two times of measurement. It was only possible to name a flow rate range for the removal of 10mm HARDOX. The spoon (Figure 9) got a hole between 12 460 tonnes and 20 021 tonnes, the deflection chute (Figure 8) between 43 636 tonnes and 67 040 tonnes and the baffle plate (Figure 6) just before 91 041 tonnes. A lifetime prediction could be realized using the simulation results for the sum of the cumulative contact energies. For the lifetime calculations the results of the impact plate were used as a basis. The prediction results are 17 857 tonnes for the spoon, 57 483 tonnes for the deflection chute and 86 104 tonnes for the baffle plate. All prediction values are between the measurement values (cf. Table 1). The same approach was used for lifetime prediction of two different "Solid State Material Driven Turbines", which were implemented at the same transfer station in a simulation (cf. Figure 5). The results of the impact plate were also used as a basis.
The first turbine tested was an overshot turbine (Figure 10) and the second a so-called transfer turbine (Figure 11).

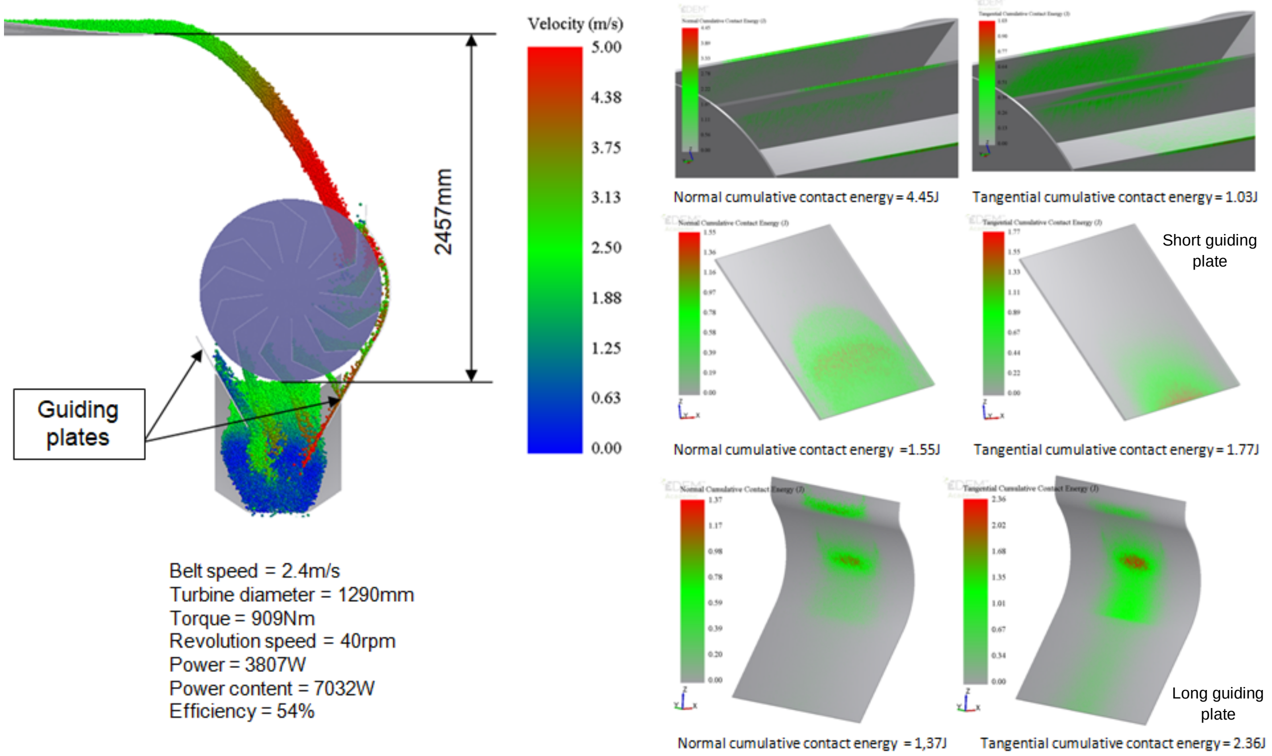


Figure 10: Simulation results overshot turbine

Both turbines use guiding plates to avoid an early discharge of particles out of the turbine area. The guiding plates also slightly increase the efficiency of the turbines. By using the overshot turbine an efficiency of about 54% and a power output of about 3.8kW can be realized. Its wear behavior is significantly lower than all other chute types which were tested before. The turbine itself exhibits a sum of cumulative contact energies in the period of record of 5.48J. Compared to the energy level of the impact plate (lowest wear level of all tested chutes) which is 13.19J, the wear value is about 2.4 times less. The wear of the used guiding plates is even lower than the wear of the overshot turbine.

The efficiency of the transfer turbine is less than the efficiency of the overshot turbine. The value is about 47%, but can be increased by the occurrent soft loading effect up to 55%. The power output is about 4.2kW. The wear level (sum of the cumulative contact energy) of the transfer turbine itself is about 10.54J and is about 20% less than the level of the impact plate. Only the cumulative contact energy respectively wear at the guiding plate is about 36% higher than the wear at the impact plate. A summary of the results is shown in Figure 12 and Table 1. The turbines have a significant wear benefit compared to the tested chutes. The statements are based on the removal of 10mm HARDOX. The maximum contact energy at the turbines is located at the edges of the turbine plates and not on the surface as on the chutes. 10mm material removal at the turbine edges will not lead to an outage of the turbine.

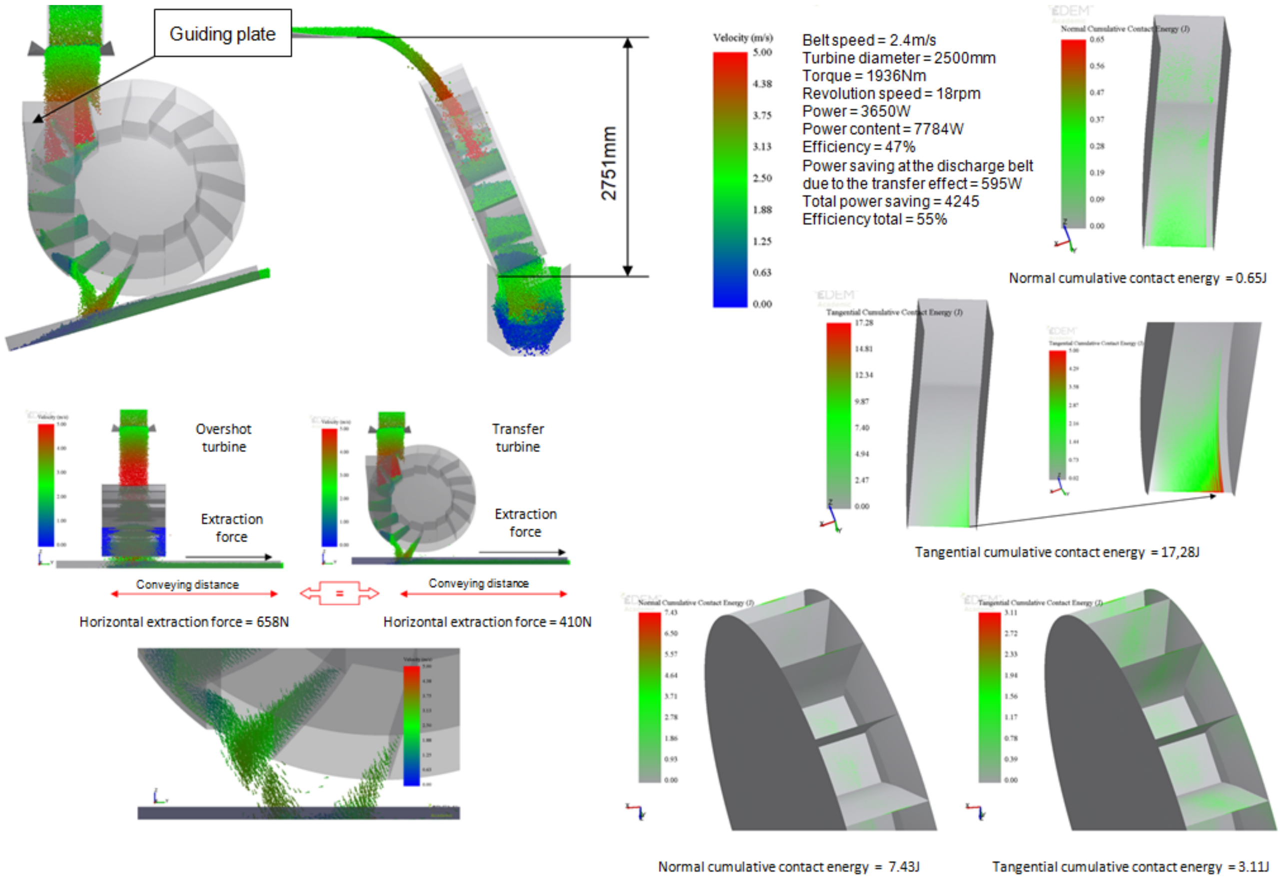


Figure 11: Simulation results transfer turbine

Table 1: Failure / live time of the different chute types (test) and live time prediction of all devices using the DEM

device	failure - measurement	Prediction DEM	Σ - contact energy DEM	multiplier live time
impact plate	186 439 t	initial value	13.19 J	10.44
baffle plate	just bevore 91 041 t	86 104 t	28.56 J	4.82
deflection chute	between 43 636 t and 67 040 t	57 483 t	42.78J	3.22
spoon	between 12 460 t and 20 021 t	17 857 t	137.71 J	1
overshot turbine	-	448 739 t	5.48J	25.13
short guiding plate	-	740 689 t	3.32 J	41.48
long guiding plate	-	659 273 t	3.73 J	36.92
transfer turbine	-	233 310 t	10.54 J	13.07
guiding plate	-	137 149 t	17.93 J	7.68

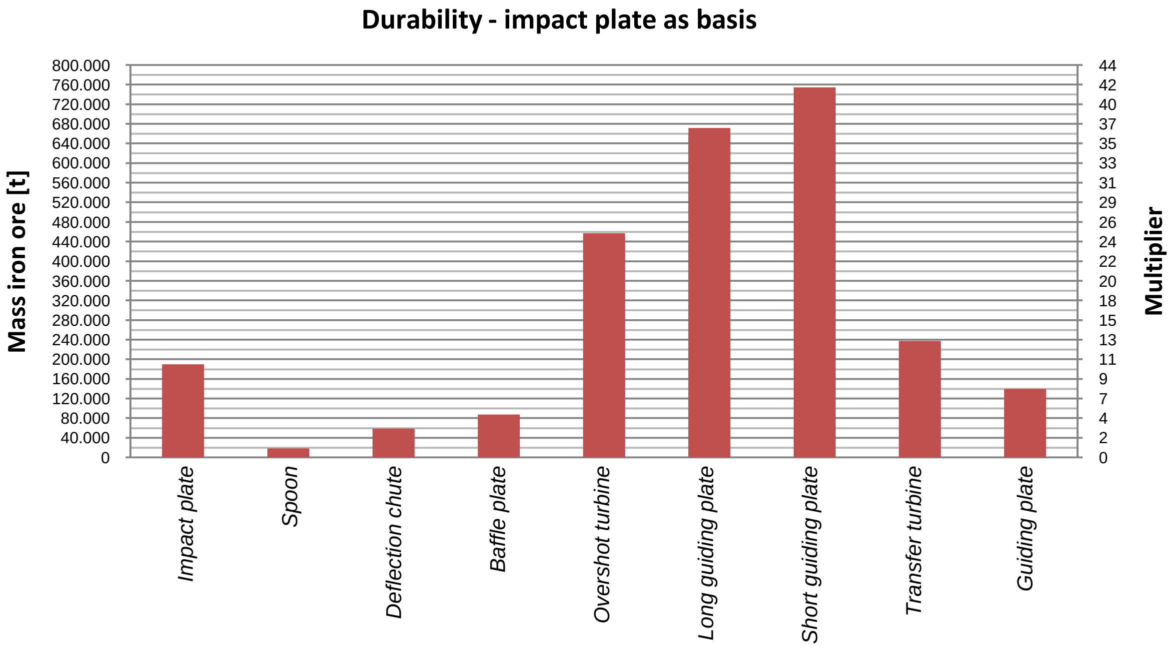


Figure 12: Summery of the durability, chutes compared with turbines and turbine guiding plates [9]

4.2. Particle breakage benefit

For the simulations shown in chapter 4.1, the kinetic energy of the particles was also analysed. Especially the transfer turbine causes less particle load (see Figure 13). This behavior could be interesting for conveying and storage processes of bulk materials, which should not break during these processes. Sinter would be a good example, because the resintering process is very energy and cost intensive.

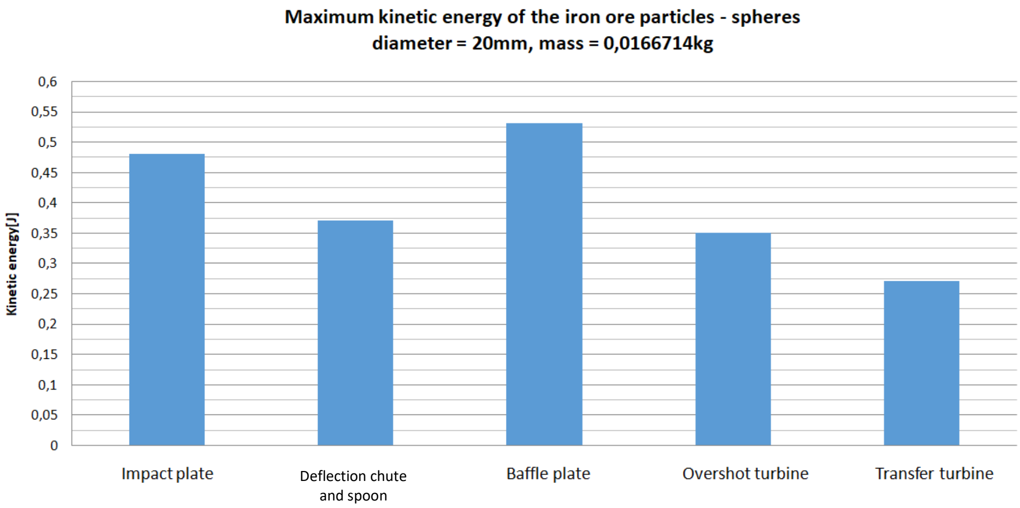


Figure 13: Maximum kinetic energy of the iron ore particles during the simulation

4.3. Particle size segregation benefit

A further interesting benefit is the avoidance of particle size segregation during discharge and transfer processes. This behavior was found during the turbine prototype tests under operational conditions and is shown in Figure 14. The picture shows the transfer of limestone from the belt conveyor into the hopper of the crusher with and without a turbine. It can be seen that without a turbine the coarse grained particles are concentrated at the opposite side of the drive pulley of the conveyor in the hopper. This behavior leads to an increased unilateral wear of the crusher and thereby to a premature failure. By using a turbine, this undesired behavior can be avoided and the service life of the crusher will be increased.

Particle segregation is often a problem, which could lead to process disadvantages of downstream industrial plants, for example during the temporary storage and transport of sinter to the blast furnace.

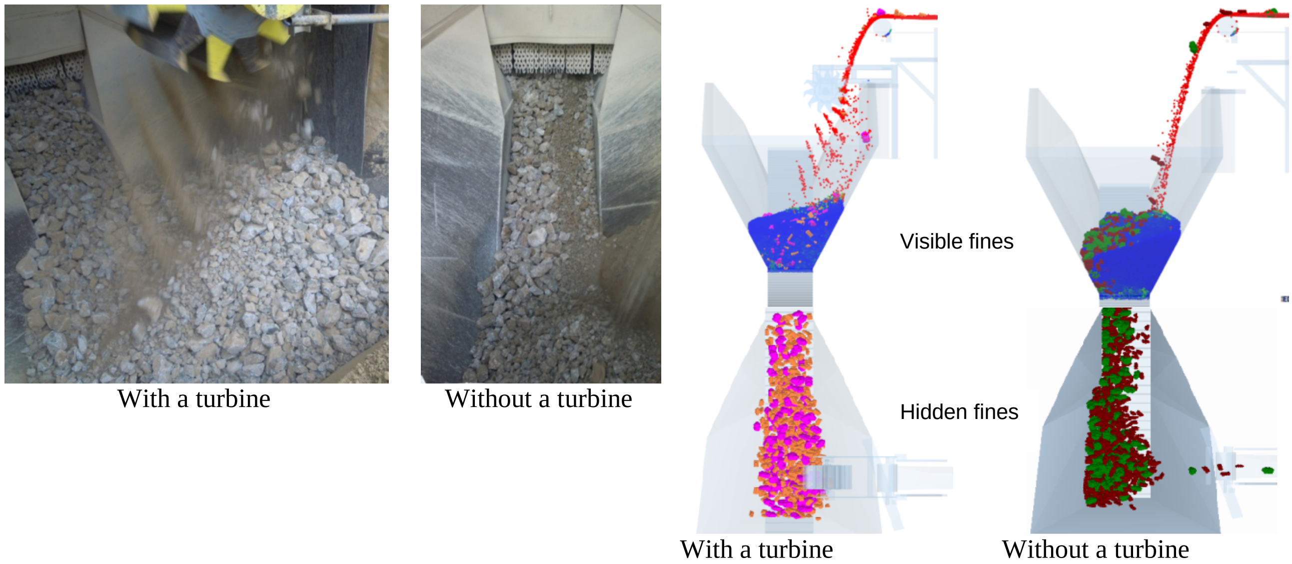


Figure 14: Particle size distribution with and without a "Solid State Material Driven Turbine"

5. Conclusion

"Solid State Material Driven Turbines" can reduce the operating costs of continuous conveying systems by recovering energy from moving bulk materials. Especially for high mass flows and/or large drop heights the turbines can harvest a lot of energy. The more energy can be recovered, the shorter the payback period of a turbine will be. Energy recovery is not the only benefit of this technology. Wear reduction compared to standard transfer or discharge chute systems can also be realized and particle segregation and degradation can be reduced. By using a so-called transfer turbine a soft loading effect at a receiving belt conveyor can be achieved. The additional benefits might be much more interesting, especially for turbines with less power output, as they can be much more economical than the actual energy recovery. The recoverable energy is available free of charge and could be better used to achieve more environmentally friendly continuous conveying systems.

6. Reverences

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