LANDTECHNIK 72(5), 2017, 247–261
DOI:10.15150/lt.2017.3170

LANDTECHNIK
AGRICULTURAL ENGINEERING

Coupled CFD-DEM simulation of separation process in combine harvester cleaning devices

Christian Korn, Thomas Herlitzius

The present paper contributes to the application of the coupled CFD-DEM approach (CFD – Computational Fluid Dynamics; DEM – Discrete Element Method) for the simulation of the separation process of grain and material other than grain (MOG) in the cleaning device of a combine harvester. The large number of influencing factors, their interactions, the wide range of scatter of properties, which are typical for biogenic particles, and the resulting complexity of the separation process require a strategic approach for the creation of a valid simulation model. The study presented in this paper investigates the separation process therefore at two levels, which differ by the degree of process abstraction. The numerical results prove the applicability of the numerical method by the comparison to corresponding experiments in general. However, deviations can also be identified which emphasize the need for further research to improve parameterization and modeling.

Key words
CFD, DEM, numerical simulation, combine cleaning device, separation of grain and MOG

The combine harvester is the central machine in the process chain of grain production. It performs the processes cutting, threshing, stratification, separation, chopping and distribution of biogenic matter in one mobile working machine. The cleaning device separates the biogenic mixture into the classes grain and material other than grain (MOG), including chaff and short straw using a vibro-fluidization process.

The load on the cleaning device has steadily increased in recent years. The reason for this is on the one hand the overall growth of throughput and on the other hand the intensified production of short straw by the use of separation rotors instead of straw walkers on high performance combines according to Rademacher (2011), Zhao (2002), Hübner (1999) and F. Beck (1999). Presently the separation process in the cleaning device of a combine harvester becomes more and more the bottleneck regarding maximal material throughput (Dahany 1994). This leads to a performance limitation below the installed capacity of the machine, due to unacceptable grain loss.

Today, functional development or optimization is predominantly performed empirically on 'trial and error' base, which is not efficient. Those tests are time-consuming, expensive, hard to reproduce and rarely enable process insight view. In addition, it is hard to characterize the flow field and particle movement by measurements. Because of the rough conditions in the functional elements (dust and high particle concentration), the availability of robust measurement equipment with sufficient accuracy is limited. The separation process is subject to the impact of a huge variety of influences and multi-layered dependencies of them (T. Beck 1992) and is still not fully understood today. Next to this,

received 24 August 2017 | accepted 23 October 2017 | published 14 November 2017

experimental machine development is hampered by the short time of harvesting period. Laboratory tests are possible throughout the year, whereas the meaningfulness and the comparability with field tests are restricted.

In recent decades numerical methods for the simulation of dispersed multiphase flows have been developed to very powerful tools (Zhu et al. 2008, Lu et al. 2015). There is a variety of different methods which were established in various fields of applications due to their characteristics, numerical effort and gain of information. Two-Fluid Models (TFM), Particle Tracking Models (PTM), Discrete Particle Models (DPM), Volume of Fluid Models (VOF), Lattice Boltzmann Models (LBM) and the Immersed Boundary Models (IBM) are among those. The approaches differ in the manner of frame of reference (Euler or Lagrange), the resolution of the phase boundary (e. g. immersed boundary methods), and the coupling between the phases. A further criterion is the resolution of length and time scales, which have very great influence on the computational effort. With a valid simulation method, it would be possible to replace or complete extensive experiments, which could decrease costs, save time, gain reproducible results and be independent of harvesting season. Compared to experiments, there are better opportunities to visualize the flow field, track particle movement and based on that, increase process understanding. Due to the possibility of parallelization of simulations, one might even be faster if the required computational resources are available.

Biogenic particles like grains or legumes as processed in the combine cleaning device are subject to complex physical properties and a large variability of these, depending on the origin of the material and the particular harvesting conditions. In most cases, these particles are non-spherical. In particular the straw particles can have a length to diameter ratio of more than 100. A biogenic particle can further be composed of different materials at different locations at the particle volume, which hampers a uniform modeling and parameterization of e. g. a contact model. Another special feature of biogenic particles is the possibility of absorbing water, which leads to a change in the physical properties and hence of the contact behavior. It is well known from literature (Freye 1980) and practical experience that mean particle moisture and particle surface moisture significantly influence the separation process. Therefore it is necessary to consider the effect of moisture within the simulation.

Present multiphase simulation methods cannot account for the above mentioned biogenic characteristics and hence are not able to provide reliable results immediately. Most of the models for particle contact or interaction with the surrounding fluid, which are available in commercial codes, have emerged from the fields of process engineering and chemical engineering. Their application to biogenic particles and the necessary approximation of particle shape cause uncertainties regarding accuracy and reliability of the results.

Nevertheless, numerical methods have been applied to several functional processes in grain harvesting technology and in particular to separation. Schwarz et al. (2012) use the DEM code ‘Pasimodo’ to compute the particle motion on the stratification pan of a combine harvester. The separation process of grain and long straw on the straw walkers of a conventional combine is in the focus of the numerical investigations of Lenaerts et al. (2014). Pförtner and Böttinger (2013) publish numerical and experimental results of separation of grain and short straw in a vertical oscillating box using composite sphere particles in a pure DEM environment. In a later publication, Pförtner et al. (2016) imprint a constant flow field which is computed by CFD to the domain. Ma et al. (2015) simulate rice-grain and straw particles in a variable-amplitude screen box in the EDEM software environment. Li et al. (2012) utilize a coupled CFD-DEM approach (EDEM by DEM-Solutions and ‘Fluent’ by ANSYS) to simulate the screening process of rice-grain and straw particles in a simplified cleaning device of a rice combine harvester. Other authors focus on the parameterization of DEM particles (Prüfer et al. 2014). The goal is to provide a valid database for users, derived from standardized or enhanced experiments, e.g. rotating drums, for a variety of agricultural materials. However, moisture, scattering particle properties and other specific characteristics of biogenic particles have not been modeled and tested in numerical investigations so far.

Objectives

The Institute of Agricultural Systems and Technology (AST) of the Technical University of Dresden (TUD) has been working on the simulation of material transport, processing and separation in the functional elements of harvesting machinery for several years. The overall objective of the research is the development of valid and efficient numerical models for their application in CAE environment. Finally the goal is to accelerate process optimization and functional development. Within this paper, the focus is set to the separation process in the combine cleaning device; the subordinate objectives can be specified as follows:

- Identification of significant parameters and their influence to numerical results
- Consideration and evaluation of biogenic particle characteristics e.g. scatter of properties, to numerical simulation
- Incorporation of mean particle moisture as an influencing factor to separation process
- Determination of driving factors for computational effort and opportunities to reduce
- Estimation of the accuracy of the simulation model by comparison with experimental results
- Exploration of sources of uncertainties and deviations and based on this, definition of further research needs

This paper gives a brief extract of the results obtained so far within the scope of the above mentioned objectives of the research.

Numerical tool

In an earlier publication, the methodology to select a provisionally suitable simulation tool is described (Korn und Herlitzius 2014). With regard to necessary two-way coupling, the available computational resources and the demand for the tracking of individual particles to determine grain loss and purity, only the coupled CFD-DEM approach is able to fulfill all of these requirements.

The software 'Star-CCM+v9.06', which is used for the numerical investigations described here, is based on a finite volume approach to simulate the fluid flow in the Eulerian framework (**CFD**). Using a statistical turbulence model, the Reynolds-Averaged-Navier-Stokes equations (RANS) are discretized and solved iteratively. The corresponding equations can be found in relevant literature (Peric and Ferziger 2008).

The Discrete Element Method (DEM), initially established by Cundall and Strack (1979), is a numerical method for the simulation of many interacting discrete objects, such as solid particles. It is based on the Lagrangian modeling methodology with inter-particle contact forces included in the equations of motion. In 'Star-CCM+v9.06', the soft-sphere approach, is used. This model allows an overlap of the colliding particles, the calculated contact force is proportional to this overlap. The utilized Hertz-Mindlin model is based on the non-linear spring-dashpot model which was derived from the Hertz-Mindlin contact theory.

Limitation of parameter range

The block diagram in Figure 1 summarizes the results of the investigations of various authors regarding parameter influences on the separation process (T. Beck 1992, Freye 1980, Srivastava et al. 1990, Huisman 1978). The diagram illustrates the complexity of the separation process and the multi-layered dependencies between target values and parameters. The relationships between parameters are indicated by arrows. In the block diagram, the limited parameter range of the simulation is shown embedded in the entire range of parameters from the real separation process. A distinction is made between input parameters for the simulation, which are directly set by the user, and those parameters, which are gained by specific models or are a superposition of different basic material and particle properties (derived properties).

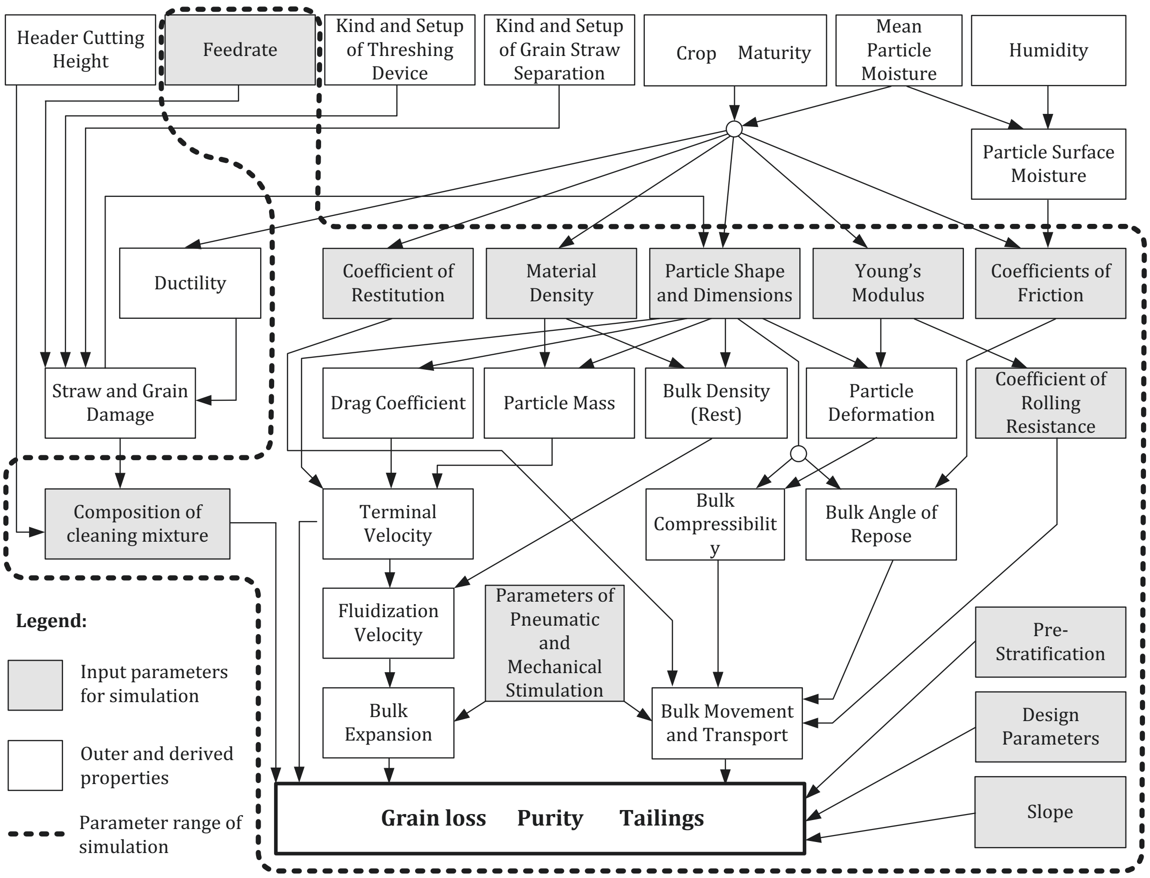

Figure 1: Correlation between target values (grain loss, purity and tailings) and process factors (ambient conditions, particle properties, etc.) of separation process; identification of direct input parameters of the simulation

Problem solving procedure

Figure 2 summarizes the applied problem solving procedure. In a 1st step the separation process is simplified in the simulation and in the experiment on a high level. This corresponds on the one hand to the size of the domain which represents a 200 × 200 mm section of the chaffer of the cleaning device. By this, the quantity of particles and the numerical effort are reduced which allows a higher number of computations. On the other hand, the separation is carried out as a batch system, not as a continuous process. The mechanical oscillation and pneumatic stimulation by air flow are pure vertical, which enables to suppress the transportation process and emphasize the working mechanisms of the separation. DEM particles are designed and parameterized based on averaged, or respectively, selected values of the literature analysis. This initial configuration contains particles for grain, chaff and short straw which are composites of spheres to approximate the real particle shape. This downsized domain is used to perform a comprehensive numerical parameter sensitivity study of the basic material, particle and interphase properties. A similar experiment is designed for comparison to numerical results. This comparison is based on macroscopic values like separation time and grain purity. Both, simulation and experiment identified the size (dimension) of grain and straw particles as the most sensitive particle parameter to separation.

Hence, in the 2nd step, a sample of chopped straw, which is primarily used in separation tests instead of chaff, is classified into length classes by a screening machine. Subsequently, a sample of each of the length-classes is separated manually into the components: straight stalks, bended stalks, heads and leaves. After that, a sample of straight stalks and bended stalks is taken and length and width of the particles is measured using digital image processing with Matlab®. Finally, the mass of the individual particles is determined and the mean particle mass and the distribution are calculated.

The distribution of the particle dimensions and related properties, e. g. mass, are implemented in ‚Star-CCM+v9.06‘ by normal distribution functions in the 3rd step.

According to T. Beck (1992), moisture cannot be related directly to the target values of the separation process; it rather influences separation via material properties. This is valid in a range of mean particle moisture, which is below a level where cohesive forces become dominant due to high surface moisture. Mean particle moisture affects next to other properties, the particle dimensions, the particle solid density, coefficients of static and dynamic friction, as well as the coefficient of restitution. The listed properties are subsequently implemented in the 4th step in the simulation as a user-defined function (UDF). The UDF expresses the properties with respect to a value for the mean particle moisture on the base of a quadratic model.

In the 5th step, the dimensions and the complexity of the domain are increased. Numerical and experimental tests of separation of grain and MOG in a segment of a cleaning device are carried out. The preferred particle design, parameterization and models from the 1st to 4th step are taken over. Previously used DEM particles for chaff are replaced by straight and bended straw particles with normally distributed size (length and diameter) in order to reproduce the chopped straw which is used in the corresponding experiments. A mechanical and pneumatic stimulation is imprinted to the system, similar to the real cleaning device, which forces separation and transportation along the sieves. A parameter study is performed taking mainly process parameters like MOG feedrate, MOG composition, intensity of mechanical and pneumatic stimulation into account. A lab test rig is designed and manufactured similar to the numerical model to perform experimental tests for comparison.

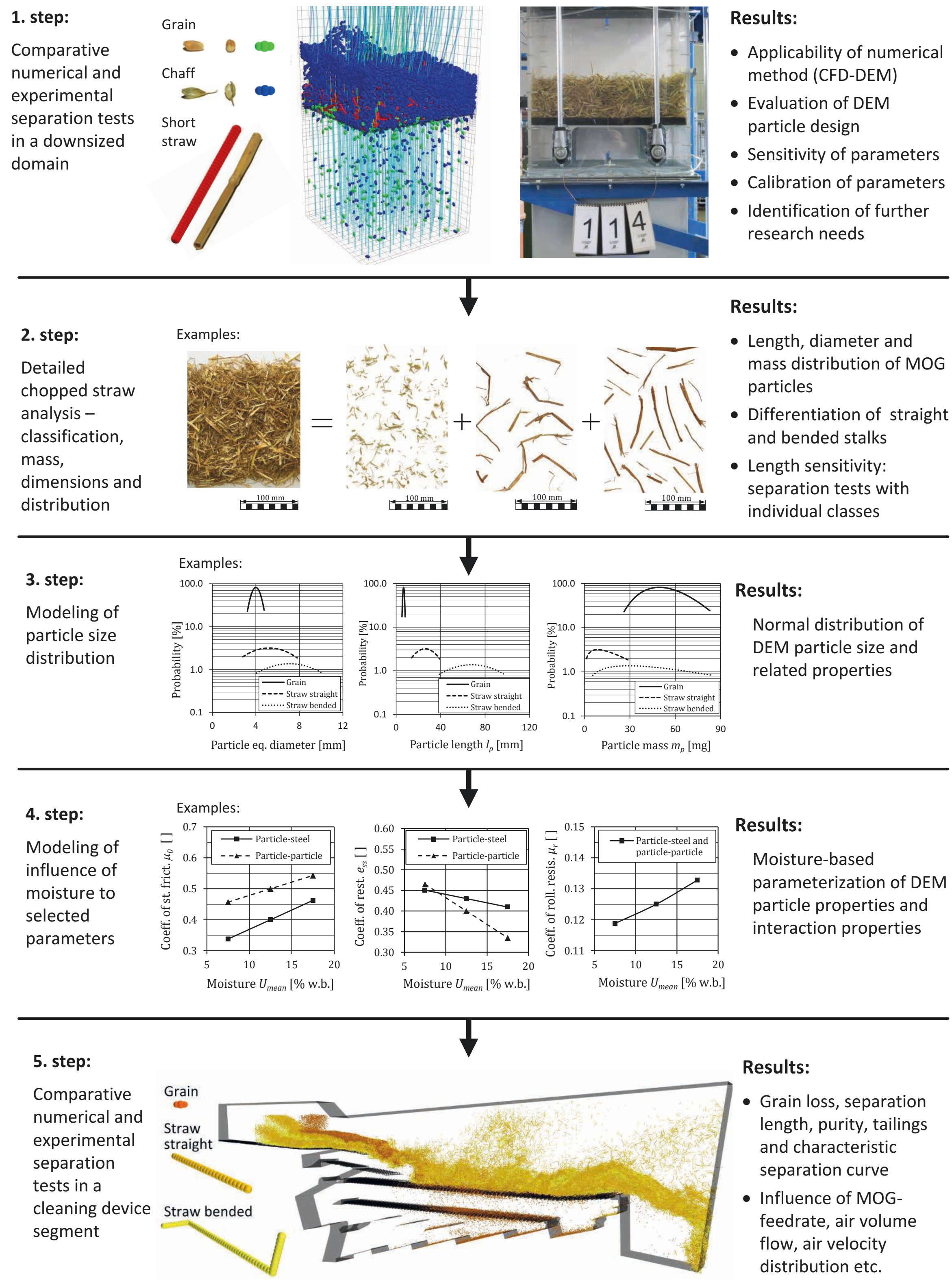

Figure 2: Problem solving procedure

Numerical model and run

The subsequent description of the simulation setup and the discussion of the results are focused on the simulations performed in the 5th step: simulation of separation in a cleaning device segment. The results of the previous steps have already been published (Korn and Herlitzius 2014). A 3-dimensional model is designed based on the geometry of a given combine cleaning device (Figure 3). The cleaning device segment has a width of 200 mm whereas the length (≈4390 mm) and all other dimensions meet the original dimensions. The louvers of chaffer and sieve represent the original geometry in detail. In order to reduce the numerical effort, the modeling of the blower is omitted. Instead, the air flow is applied to the main channel which serves chaffer, sieve and 2nd cascade, and the secondary channel which serves the 1st cascade. The distribution and direction of air flow at the cross-section of the respective channel is taken over from previously performed numerical simulations and experiments. To further reduce complexity, the typical oppositely directed movement of chaffer and sieve is neglected. The entire domain oscillates with a frequency, amplitude and direction according to chaffer.

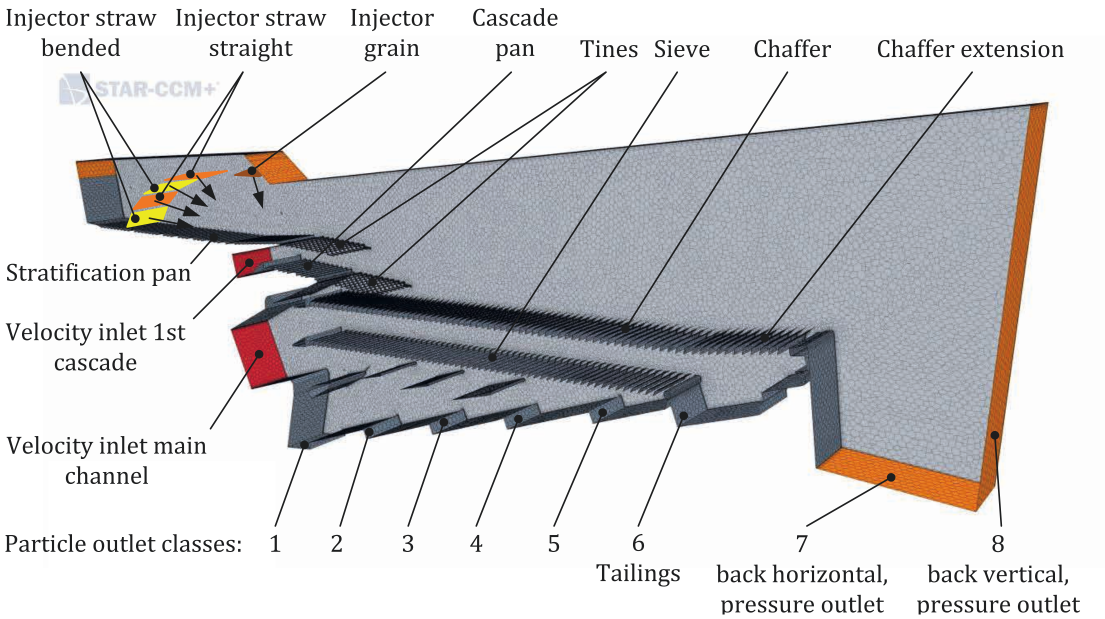

Figure 3: CFD-DEM model of cleaning device segment

The design of the bottom of the numerical model differs from the original cleaning device which has bellies for grain and tailings auger. Instead, the bottom is built of 6 steps representing a facility to classify the separated particle along sieve and chaffer. Whereas it would be possible to figure out a continuous separation curve in the simulation, this classification is needed with regard to the experimental test rig. Table 1 lists the essential settings and models of the numerical simulations of the cleaning device segment.

Table 1: Model setup (standard configuration)

Property	Value
Domain width	200 mm
Number of mesh cells	1.33 Mio
Wall friction of sidewalls	Without friction
Air density (20 °C)	ρ_f = 1.184 kg/m³ (incompressible)
Air dynamic viscosity (20 °C)	$\mu = 1.85508 \cdot 10^{-5}$ Pa s
Gravity	$g = 9.81\ m/s^2$
Governing equations	URANS
General Solving Approach	Coupled
Spatial Discretization	2nd-order upwind, implicit
Temporal Discretization	2nd-order implicit
Physical time step	0.001 s
Solver	AMG linear solver
Turbulence	Realizable k- two-layer with all y+ wall treatment
DEM particles	Sphere composites, stiff
DEM drag force model	Gidaspow
DEM drag torque model	Sommerfeld
Particle-fluid interaction	Two-way coupling
DEM contact model	Hertz-Mindlin
Rolling resistance model	Force proportional
Mass flow relation grain : straw in %	70 : 30

As shown in Figure 3, straight and bended straw particles are injected into the cleaning device segment in two alternating layers above the stratification pan. Due to limitations of particle injector definition of the applied software environment, a mixed injection is not possible. It is confirmed by preliminary investigations that during the movement along stratification pan and cascades, straight and bended straw particle intermix to a sufficient level before entering chaffer. Grain is fed on top of the straw layer. This kind of feeding represents the worst case scenario for the cleaning device and is very easy to reproduce with the experimental test rig. Simultaneously with the start of the movement of the numerical domain, the injection of straight and bended straw particles begins at $t = 0$ s. Position and delayed start of grain injection at $t = 0.3$ s ensure that grain falls on top of a developed straw layer. After a physical time of about $t = 10$ s, the system shows a steady state behavior. The material layer above chaffer has fully developed and the grain loss has converged to a certain value. Now, the period for data evaluation, which takes $\Delta t = 2$ s starts. At a physical time of $t = 12$ s the simulation is stopped. Each run takes between ≈ 21 000 CPU hours (for low MOG feedrate) and ≈ 37 000 CPU hours (for high MOG feedrate) to achieve 12 s of physical time. By utilizing 96 cores in parallel the solver total elapsed time is between 218 and 385 hours for a run.

Results and discussion

The entire test program carried out so far contains as parameters the relative MOG feedrate, the fluid velocity at main channel and secondary channel (multiplied with factors representing different fan turning speeds), the mass relation of bended straw to straight straw, the mean MOG particle size, the distribution of MOG particle size, the turbulent intensity at main channel inlet, the grain moisture and straw moisture based on the derived models, the MOG particles density and Young's modulus, sieve and chaffer opening width, the oscillation frequency and the oscillation amplitude among others. Here, only an excerpt of the results can be given. Figure 4 shows an example of the CFD-DEM simulation at a physical time of 12 s. The material layer is fully developed. Individual straw particles are carried out pneumatically. The air flow is indicated by streamlines.

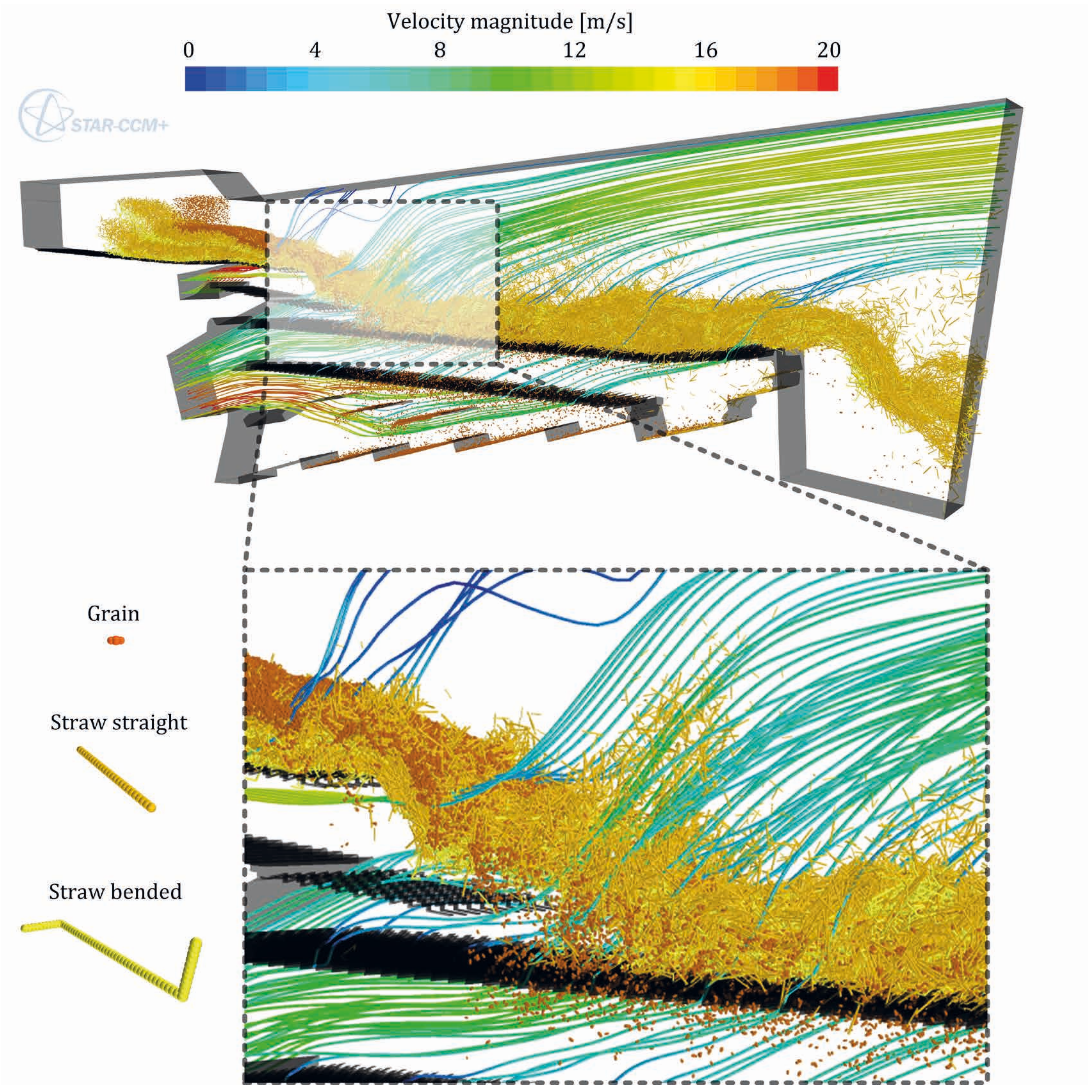

Figure 4: Exemplary graphical representation of results: DEM particles (particle legend not in scale) and streamlines (colored by fluid velocity)

Within the test program, the particle injector diameter of the MOG particles (straight and bended straw) is multiplied with a factor which is varied on the levels of 0.7, 0.8, 0.85, 1.0, 1.15, 1.2 and 1.3, while 1.0 represents the nominal size of the straw particles based on the chopped straw analysis of 2nd step described above. The size of grain is kept constant. As Figure 5 shows, the grain loss is significantly affected by the factor of straw particle injector diameter. The standard deviation of test repetitions is added to the data to indicate the significance. The use of greater straw particles causes lower grain loss. This behavior is assumed to be based on the larger gaps between the coarser straw particles, facilitating the grain to migrate through the straw layer. Those gaps get tighter for smaller particles, even if the mean void fraction is almost constant over the range tested particle size.

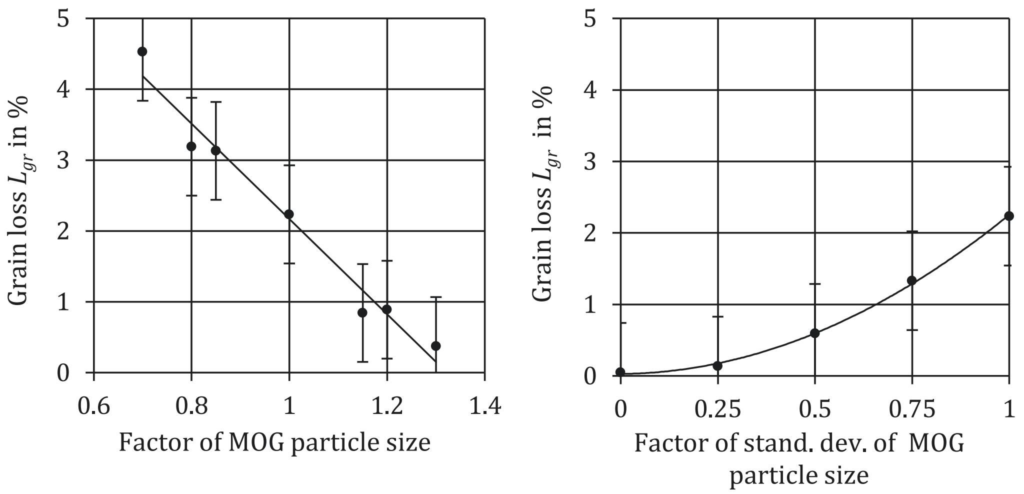

Figure 5: Results of simulation – left: grain loss as affected by factor of MOG particle size,
right: grain loss as affected by factor of standard deviation of MOG particle size,
(MOG feedrate q_{MOG} = 1.79 kg/(s m), Factor of fluid velocity at main inlet FFV_{main} = 1)

Based on the chopped straw analysis and particle modeling of the 2nd and 3rd step from above, the particles are injected using a normally distributed diameter, which influences the length of the DEM particles in the same way. The distance of the individual spheres of the composite particles is relative to particle injector diameter. Within the test program, a factor of 0, 0.25, 0.5 and 0.75 is multiplied to the definition of the standard deviation of particle equivalent (injector) diameter of straight and bended straw particles. A factor of 1 represents the nominal standard deviation based on the results of 2nd step. The standard deviation of grain injector diameter is not varied. As demonstrated by Figure 5 for zero distribution (all particles of a class have the same size), the grain loss is almost zero. For rising values of standard deviation, the grain loss increases over-proportional. This confirms the above statement that if only large particles are present in the system, the separation proceeds comparatively easy. If, on the other hand, smaller particles are added, these fill the gaps between the large particles and thus make the migration of grain through the straw layer more difficult.

The sample of chopped straw analyzed in the 2^{nd} step is composed of 73 % straight and of 27 % bended straw particles, which is used as standard configuration for the numerical tests. By the variation of the ratio of bended straw particles and straight straw particles, the correlation to grain loss is evaluated. The effect of the percentage of bended straw particles is tested numerically in a range of 0–30 % and the results are presented in Figure 6. The correlation between the percentage of bended straw and grain loss can be approximated by the given exponential function. Up to about 10 % of bended straw particles, the correlation to grain loss is characterized by a moderate slope. A further increase of the percentage of bended straw particle causes a disproportionate rise of grain loss. In conclusion, the bended straw particles are a significant factor for the separation behavior. Their percentage can be used to adjust the numerical model to fit the experiments.

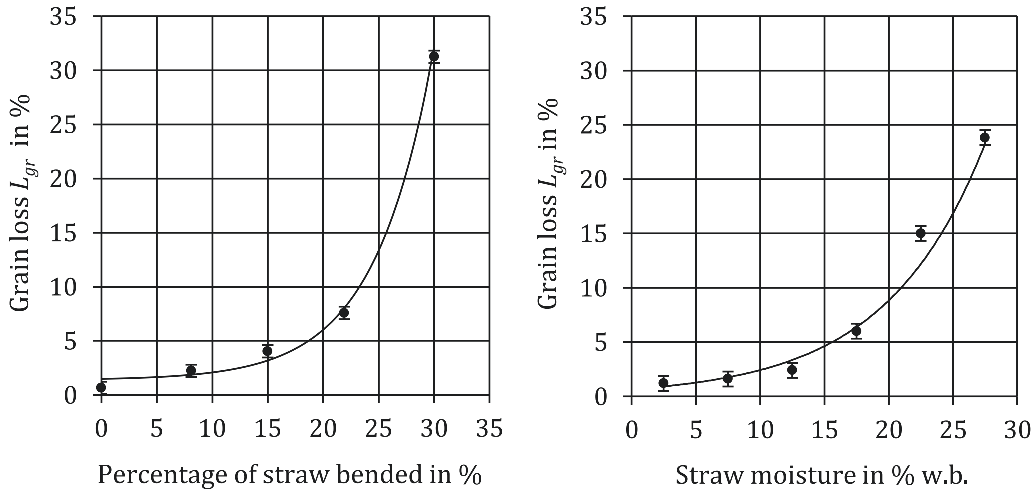

Figure 6: Results of simulation – left: grain loss as affected by mass percentage of bended straw, right: grain loss as affected by straw moisture (MOG feedrate q_{MOG} = 1.79 kg/(s m), Factor of fluid velocity at main inlet FFV_{main} = 1)

In order to study the effect of the straw moisture model to grain loss also in the functional outer limits, the range of moisture investigated here exceeds the practical range of harvesting conditions. Values between 2.5 and 27.5 % are tested. As shown in Figure 6, the influence of straw moisture can be well described with an exponential function. For the low range of moisture, the grain loss slightly starts to grow. At a moisture of about 12.5 % the grain loss grows rapidly up to L_{gr} = 24 %. The experimental test program carried out so far does not include tests with different MOG moisture. Without a base for experimental comparison, it can just be concluded that the influence of straw moisture is plausible and reflects the practical experience generally.

An experimental test rig is designed and manufactured in order to validate the numerical model of the cleaning device segment (Figure 7). The section of the CFD-DEM model is indicated supplementary in the scheme. In contrast to the simulations, the test rig has a width of 700 mm to keep the wall effects of the sidewalls low.

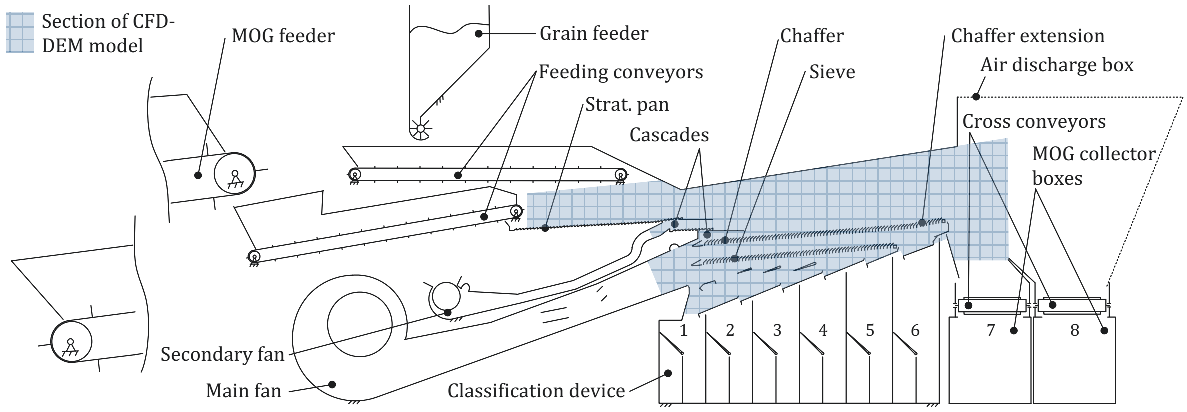

Figure 7: Design of experimental cleaning device test rig and indication of section of CFD-DEM model

Figure 8 shows a snapshot of the simulation and a corresponding experiment for a relative MOG feedrate of q_{MOG} = 2.38 kg/(s m), which is equal to a MOG feedrate of 12 t/h for full system width. A pure visual comparison indicates on the one hand a similar height and decompaction of the material layer. On the other hand, simulation and experiment show the presence of airborne particle at the same locations, which are immediately behind the cascades and above chaffer extension.

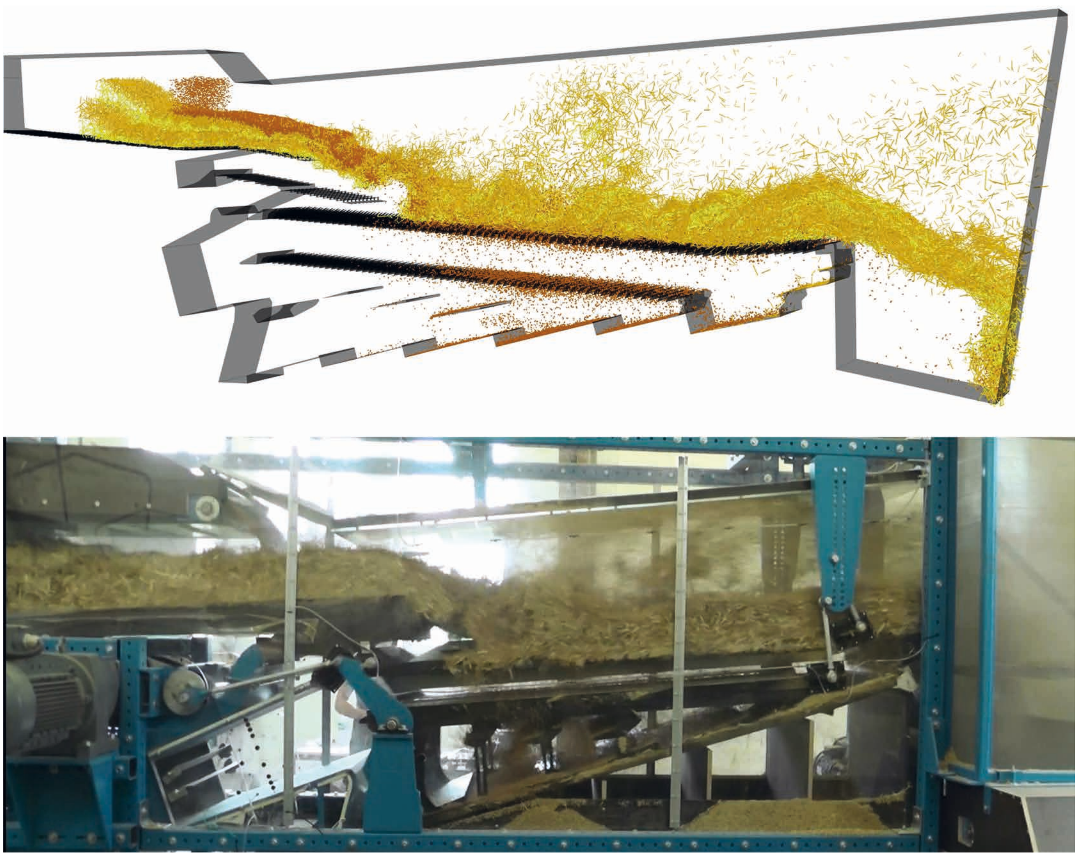

Figure 8: Snapshots of numerical separation (upper picture) and experimental separation (lower picture) in a combine cleaning device segment at stationary period for rel. MOG feedrate of 2.38 kg/(s m)

The interaction between relative MOG feedrate and the factor of fluid velocity at main inlet, which represents a factor multiplied to nominal fan turning speed, in terms of grain loss are shown in Figure 9 for experimental and numerical results. The characteristic curves show commonly a shift of the optimum to higher fluid velocities for increasing MOG feedrate, indicated by the dashed line.

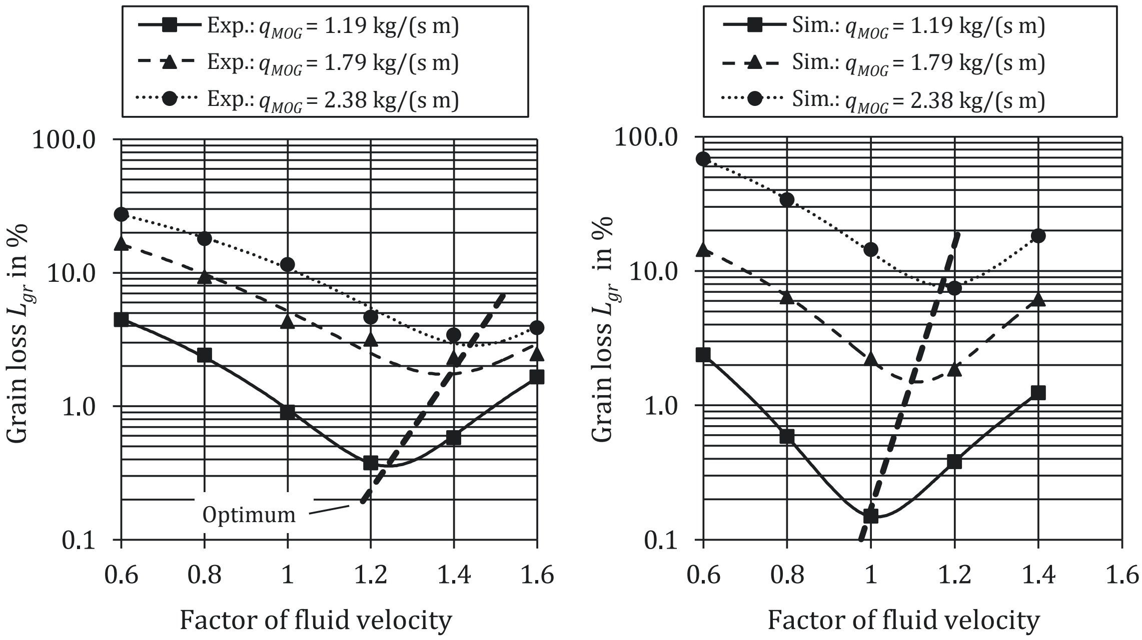

Figure 9: Interaction of relative MOG feedrate and fluid velocity at main inlet on grain loss; comparison of experimental results (left) and numerical results (right); factor of fluid velocity represents a factor multiplied to nominal fan turning speed

In the experiment, the optimum is at a higher fluid velocity in general, and is more dependent of the MOG feedrate. In general, the simulation matches the experiment very well for low and moderate MOG feedrate. However, major deviations occur for high MOG feedrate, e. g. q_{MOG} = 2.38 kg/(s m). Here, the simulation is much more sensitive to fluid velocity which can be derived from the significantly higher grain loss at the outer limits of the characteristic curve. At this point there is a considerable need for further improvement. However, corresponding to all simplifications of the numerical model, the abstraction of the DEM particles, the variety of parameters and all initial uncertainties, it can be concluded that Figure 9 is the fundamental prove of the method for the application to separation process.

Conclusions

The coupled CFD-DEM approach is suitable to simulate the separation process of grain and MOG in combine harvester cleaning devices. A distinction between straight and bended DEM straw particles is necessary in the simulation to meet the resistance of the material layer to grain passage. The ratio between bended and straight straw particles is suitable to fit the simulation to the experiment. Further, the size of the DEM-MOG particles, as well the distribution of size is of major influence to grain loss. The applied moisture model produces plausible results but still needs to be validated by experimental results. Simulation shows lower grain loss for coarser particles, which is opposite to experimental and practical experience. Hence, investigations with extended scattering range of the

MOG particle properties are taking place currently, in order to further improve the resistance of the MOG layer to the migration of grain. Further the simulation appears to be more sensitive to changes of air volume flow than the experiment. At present, tailored drag coefficients for the DEM grain and straw particles are determined by advanced CFD simulations, taking the shape of the DEM particles and their direction to mean air flow into account.

References

Beck, F. (1999): Simulation der Trennprozesse im Mähdrescher. Fortschritt-Berichte VDI Reihe 14 Nr. 92, VDI-Verlag, http://opus.uni-hohenheim.de/volltexte/2014/905/

Beck, T. (1992): Meßverfahren zur Beurteilung des Stoffeigenschaftseinflusses auf die Leistung der Trennprozesse im Mähdrescher. Fortschritt-Berichte VDI Reihe 14 Nr. 54, VDI-Verlag, https://www.uni-hohenheim.de/qisserver/rds?state=medialoader&objectid=8298&application=lsf

Cundall, P. A.; Strack, O. D. L. (1979): A discrete numerical model for granular assemblies. Geotechnique 29, pp. 47–65

Dahany, A. (1994): Verbesserung der Leistungsfähigkeit luftdurchströmter Schwingsiebe bei der Korn-Spreu-Trennung im Mähdrescher durch Optimierung der Luftverteilung, Dissertation, Universität Hohenheim, Forschungsbericht Agrartechnik des Arbeitskreises Forschung und Lehre der VDI-MEG Nr. 245

Freye, T. (1980): Untersuchungen zur Trennung von Korn-Spreu-Gemischen durch die Reinigungsanlage des Mähdreschers. Dissertation, Stuttgart-Hohenheim, Selbstverlag

Hübner, R. (1999): Entwicklung eines Modells zur Auslegung einer rotierenden Reinigungseinrichtung im Mähdrescher, Dissertation, TU Dresden

Huisman, W. (1978): Moisture content, coefficient of friction and modulus of elasticity of straw in relation to walker losses in a combine harvester. ASAE publication 1–78, pp. 25–29

Korn, C., Herlitzius, T. (2014): Strömungssimulation als Entwicklungswerkzeug in der Mähdruschtechnik – Potential, Numerische Verfahren und Validierung. VDI-Bericht 2226, VDI-MEG Tagung LAND.TECHNIK, Berlin

Lenaerts, B.; Aertsen, T.; Tijskens, E.; De Ketelaere, B.; Ramon, H.; De Baerdemaeker, J.; Saeys, W. (2014): Simulation of grain–straw separation by Discrete Element Modeling with bendable straw particles. Computers and Electronics in Agriculture 101, pp. 24–33

Li, H.; Li, Y.; Gao; F. (2012): CFD-DEM Simulation of material motion in air- and screen cleaning device. Computers and Electronics in Agriculture 88, pp. 111–119

Lu, G.; Third, J. R. Müller; C. R. (2015): Discrete element models for non-spherical particle systems: From theoretical developments to applications. Chemical Engineering Science 127, pp. 425–465

Ma, Z.; Li, Y.; Xu, L. (2015): Discrete-element method simulation of agricultural particles' motion in variable-amplitude screen box. Computers and Electronics in Agriculture 118, pp. 92–99

Peric, M.; Ferziger; J. H. (2008): Numerische Strömungsmechanik. Berlin, Heidelberg, Springer Verlag

Pförtner, J.; Böttinger, S. (2013): Validierungsstrategie für DEM-Modelle von Mähdrescherbaugruppen. VDI-MEG Kolloquium Landtechnik, Hohenheim 12./13.09.2013, Heft Nr. 40, S. 27–32

Pförtner, J.; Böttinger, S.; Schwarz, M.; Schürmann, L. (2016): Simulation des Entmischungsprozesses von Korn und Kurzstroh. VDI-Tagung LAND.TECHNIK 2016, Köln, 22.–23. November 2016, VDI-Bericht Bd. 2273, S. 361-367

Prüfer, A.; Englisch; J. Schultze, M.; Meinel, T. (2014): ADALS – Beitrag zur DEM-Partikelsimulation in der Landmaschinentechnik. Landtechnik 69(4), S. 180–184, DOI: http://dx.doi.org/10.15150/lt.2014.187

Rademacher, T. (2011): Druschfruchternte – Wettbewerb der Systeme nimmt zu. Eilbote 13, S. 10–13

Schwarz, M.; Pförtner, J.; Mümken, P.; Böttinger, S. (2012): Gutbewegungsvorgänge auf dem Vorbereitungsboden, Erfahrungen mit der DEM-Software PASIMODO. VDI-Tagung LAND.TECHNIK 2012, Karlsruhe, 6.–7.11.2012, VDI-Bericht Bd. 2173, S. 363–369

Srivastava, A. K.; Mahoney, W. T.; West, N. L. (1990): The effect of crop properties on combine performance. Transactions of ASAE 33(1), pp. 63–72

Zhao, Y. (2002): Einfluss mechanischer und pneumatischer Parameter auf die Leistungsfähigkeit von Reinigungsanlagen im Mähdrescher. Dissertation, Universität Hohenheim, Forschungsbericht Agrartechnik des Arbeitskreises Forschung und Lehre der VDI-MEG Nr. 387

Zhu, H. P.; Zhou, Z. Y.; Yang, R. Y.; Yu, A. B. (2008): Discrete particle simulation of particulate systems: A review of major applications and findings. Chemical Engineering Science 63(23), pp. 5728–5770

Authors

Dipl.-Ing. Christian Korn is scientific staff member and **Prof. Dr.-Ing. Thomas Herlitzius** is head of the Institute of Natural Materials Technology (INT) at the Technical University of Dresden, Bergstraße 120, 01069 Dresden, e-mail: korn@ast.mw.tu-dresden.de.

Acknowledgment

The computations were performed on the Bull HPC-Cluster of the Centre of Information Services and High Performance Computing (ZIH) of the Technical University of Dresden. Special thanks for the generous allocation of computer time.