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Numerical study of air flow in a combine cleaning shoe

High material throughput of state of the art combine harvesters and raising quantity of non-conventional separation systems lead to an increased load for the cleaning shoe. In addition to the mechanical part, the separation success depends largely on the pneumatic decompaction. Computational fluid dynamics (CFD) is used to determine the distribution of air volume flow to individual functional elements (cascades and chaffer/sieve) as well as the distribution of air velocity along chaffer and sieve. The methods to include the chaffer and the air flow resistance of material layer are presented and discussed. The computational results confirm the experience of unfavorable flow conditions in case of loaded cleaning shoe and are used to evaluate the effect of design modifications.

Keywords
Cleaning device, combine harvester, air stream, simulation, CFD, material layer

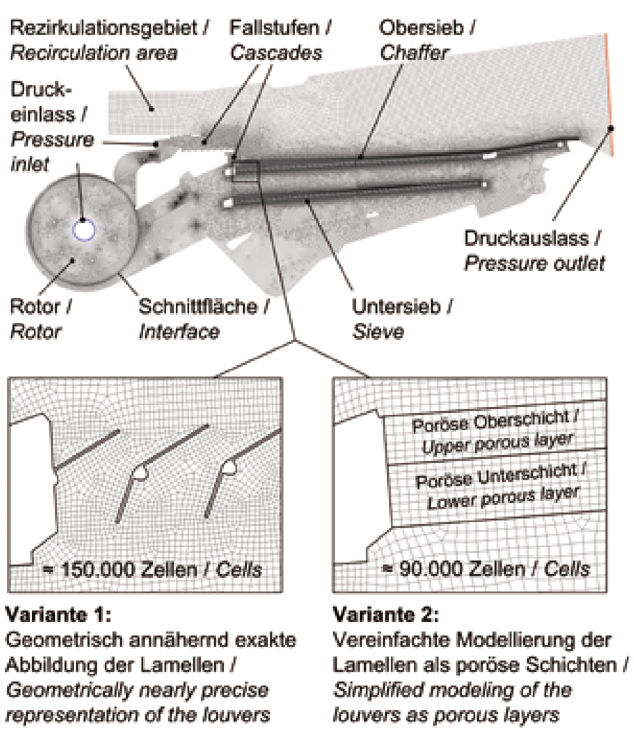
Abstract
Landtechnik 68(2), 2013, pp. 83–88, 7 figures, 1 table, 12 references

Today combine cleaning shoes are still present in their conventional design. In general the airflow required at sieves and cascades is provided by a central fan, then spread over multiple flow channels and distributed to the shoe elements. The flow direction and velocity in the cascades, the distribution of flow velocity and pressure along chaffer and sieve, as well as the division of volume flow rate to chaffer and sieve are the important pneumatic parameters [1–6]. Especially at the chaffer the flow conditions are unfavorable in loaded mode. At the front of the chaffer, where a high material layer and thus a high flow resistance is present, the flow velocity is often too low to achieve a sufficient decompaction. On the other hand grain is blown out at the end of the chaffer due to the thinner material layer and high flow velocity. With flow conditions adjusted to the material flow, it would be possible to increase the separation efficiency by 30 % [2]. The application of flow measurement equipment in loaded cleaning shoe conditions (during separation process) is difficult because of a high amount of particles in the flow. As an alternative to the experiment, the computational fluid dynamics (CFD) could be used to study flow conditions. Due to high reproducibility, excellent visualization capability and low effort for modifications, CFD seems to be a suitable development tool for the present problem. Relevant investigations are currently limited to a few specific cases [7, 8].

Structure of numerical models

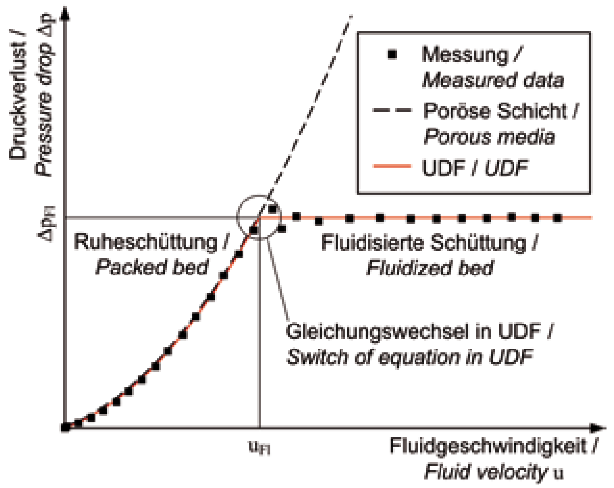
Due to the complexity of the considered cleaning shoe and its spatial dimensions it is necessary to simplify the solution domain in order to reduce numerical effort. A two-dimensional longitudinal section is created including the entire cleaning shoe and the fan. The computational model is built on 1 : 1 scale to the

Fig. 1



Mesh, boundary conditions and representation of louvers

Fig. 2



Modeling of fluid flow resistance of material layer

Table 1

Nomenclature

Symbol	Erläuterung/*Description*	Einheit/*Unit*
C_1	Reibungswiderstandsfaktor *Viscous resistance factor*	m^{-2}
C_2	Trägheitswiderstandsfaktor *Inertial resistance factor*	m^{-1}
d_K	Korndurchmesser *Grain diameter*	m
g	Gravitation *Gravity*	$m\ s^{-2}$
h'	Strömungsweg *Flow distance*	m
k_l	Laminarkonstante *Laminar constant*	-
k_t	Turbulenzkonstante *Turbulence constant*	-
p	Druck *Pressure*	$N\ m^{-2}$
s_i	Quellterm *Source term*	$kg\ m^{-2}\ s^{-2}$
u_i	i-te Komponente der Geschwindigkeit *i-th velocity component*	$m\ s^{-1}$
u_l	Luftgeschwindigkeit *Air velocity*	$m\ s^{-1}$
x_i	i-te Koordinate *i-th coordinate*	m
ε	Spezifisches Hohlraumvolumen *Specific void fraction*	-
λ	Auflockerungsfaktor *Decompaction factor*	-
ρ_l	Luftdichte *Air density*	$kg\ m^{-3}$
ρ_s	Stoffdichte *Material density*	$kg\ m^{-3}$
ν	Kinematische Viskosität *Kinematic viscosity*	$m^2\ s^{-1}$

original and is represented in **Figure 1**. The gradients of flow are expected to be high near the louvers of chaffer and sieve. The mesh size needs to be customized in this area. Hence, two different computational models are created, which differ regarding the modeling of chaffer and sieve. One model is characterized by a geometrically nearly precise representation of the louvers, the other one by modeling chaffer and sieve as porous layers. The number of grid cells can be reduced significantly by doing this.

Flow resistance of material layer

There are numerous ways to include a material layer or the influence of a material layer on the air flow in the calculation. Initially a multiphase simulation is not performed due to the high numerical effort and the insufficient validated or non-existing models and parameters for biogenic particles. In contrast, the use of the source term in the momentum equations to model the flow resistance represents a good compromise of the informational content of the results and the numerical effort. On the one hand the parameterization can be achieved with fixed values, corresponding to the already implemented model of a porous layer in Ansys Fluent. Alternatively, a User Defined Function (UDF) can be used to create a dependency between individual parameters and the flow variables (e. g. fluid velocity). **Figure 2** illustrates the relationship between the pressure loss and the fluid velocity for both resistance models and shows a measured fluidization curve of wheat as an example. The fluidization of a real bed is characterized by the occurrence of a fluidization point, from which the bed has fluid-like properties. The pressure drop over the material layer remains constant with increasing fluid velocity. By using an UDF it is possible to allocate corresponding equations to the physical bed states and to fit the real curve very well.

The quadratic part of the equation for both models is based on the equation of Ergun and Orning [9] (Equation 1). It allows the calculation of the specific pressure drop over a layer of granular material. Assuming an isotropic material layer it is possible to determine the input parameters C_1 (friction resistance factor) and C_2 (inertial resistance factor) for the calculation program by comparing the coefficients (**Table 1**). Equation 2 is the formulation of the source term of the momentum conservation equation when using a porous layer in Ansys Fluent. The linear (constant) part of the fluidization curve can be estimated with Equation 3.

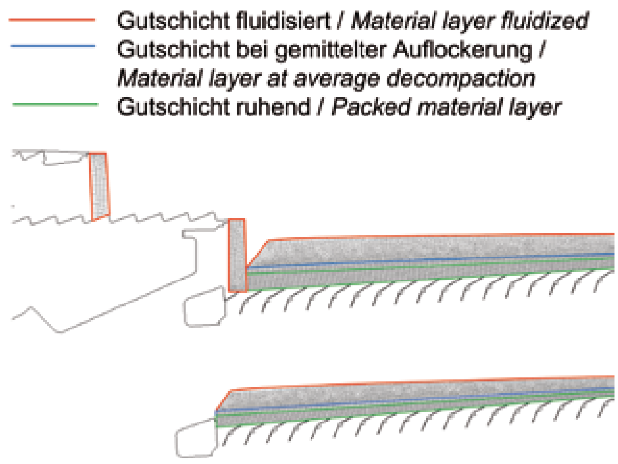
$$\frac{\Delta p}{h'} = k_l \frac{(1-\varepsilon_K)^2}{d_K^2\, \varepsilon_K{}^3} \rho_l\, \nu\, u_l + k_t \frac{(1-\varepsilon_K)}{d_K\, \varepsilon_K{}^3} \frac{1}{2} \rho_l\, u_l^2 \quad \text{(Eq. 1)}$$

$$s_i = \frac{\partial p}{\partial x_i} = -\left(C_1\, \rho_l\, \nu\, u_i + C_2 \frac{1}{2} \rho_l\, |u|\, u_i\right) \quad \text{(Eq. 2)}$$

$$\frac{\Delta p}{h'} = g(1-\varepsilon_0)(\rho_s - \rho_l) \quad \text{(Eq. 3)}$$

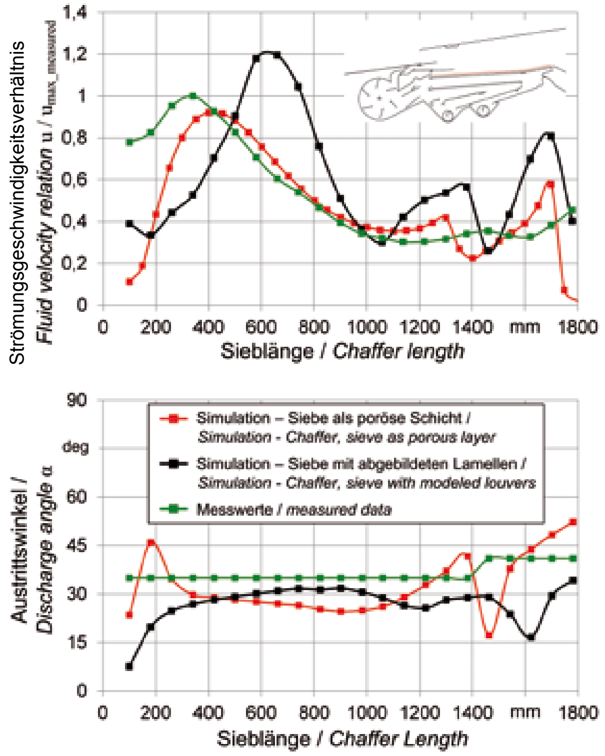
$$\varepsilon_K = \lambda\, \varepsilon_0 \quad \text{(Eq. 4)}$$

Fig. 3



Material layer and phases of decompaction

Fig. 4



Top: To maximum value of measured data normalized absolute fluid velocity. Bottom: Discharge angle. Both: Longitudinal distribution along unloaded chaffer

The range of validity of Equation 1 is limited to packed beds of pure grain, so the specific void fraction ε_κ needs to be extended to the periodically loosened cleaning mixture, which is present in the combine. For this the decompaction factor λ according to Hübner [10] and Freye [1] can be used, whereby the specific void fraction for packed beds is denoted with ε_0 (Equation 4). The decompaction factor λ is a continuous quantity, which is periodically changing because of the oscillating movement of the sieves. Additionally it depends on the intensity of the pneumatic and mechanical stimulation. Two essential simplifications are made in the numerical studies described below:

- The unsteady decompaction is not represented directly. Instead of that, the numerical analysis is based on three characteristic decompaction conditions. With the results for a packed bed, a material layer with time-averaged decompaction and a fluidized material layer it is assumed to have information to describe the flow conditions in a representative manner.
- Lehmann confirms [11] experimentally that the flow resistance of the material layer depends on the grain fraction K_{KA}. For the same material layer height, cleaning mixtures with high grain content cause a higher flow resistance than those with smaller grain fractions. This means for the simulation, that the parameterization is used to be based on grain fraction dependent material layer properties. Due to the motion model to determine the decompaction factor λ is based on material layer of pure grain, it seems to be practical not to increase the complexity of the model and the parameterization. So the calculation is based on a material layer of pure grain. Thus the material layer can be parameterized uniformly and the MOG (material other than grain) is added in terms of its mass to the material layer.

The material layer is integrated geometrically in the simulation model by the definition of separate mesh zones above the sieves. The source terms of the momentum equations of the associated mesh cells can be assigned with the mentioned flow resistance models. The specification of the material layer height is done by the so called residual-kernel-function by Schreiber [12]. **Figure 3** illustrates the expansion of the material layer caused by the mechanical and pneumatic stimulation for the relevant characteristic decompaction conditions.

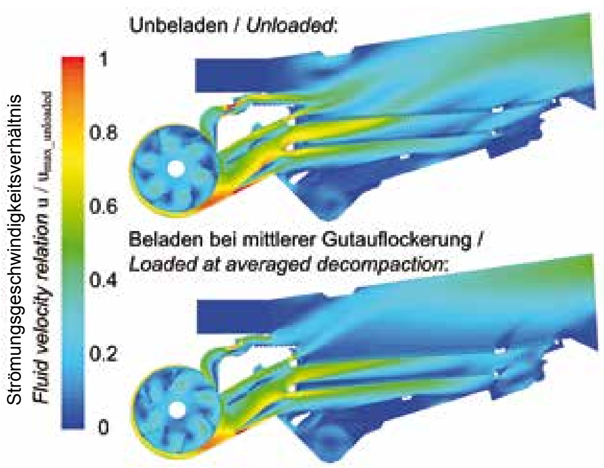
Solution setup

Since the Mach number Ma = 0.3 is not exceeded in the solution region, the fluid can be assumed to be incompressible. Basis of the solution are the RANS equations (RANS - Reynolds Averaged Navier Stokes) for the averaged turbulent flow. For turbulence, the RNG k-ε model (RNG - renormalization group) is chosen. This is an extension of the standard k-ε model and it is more accurate in complex flows, as well as in the case of separated flow and vertebration. The spatial discretization of the flow variables is performed by a 2nd order upwind-difference-scheme, the temporal discretization is implicit and also of 2nd order.

Results

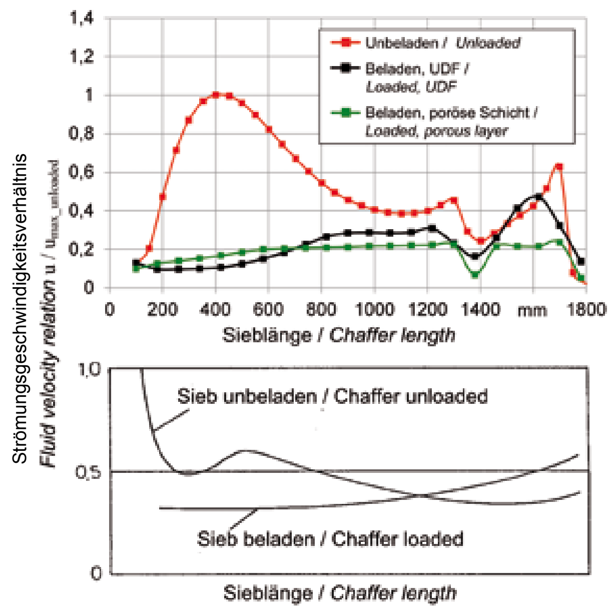
The study of the cleaning shoe under unloaded conditions confirms the suitability of the porous layer as a model for the sieves. Applicable quantities for the flow resistance of the lower and upper part of the louvers, shown in **Figure 1**, can be

Fig. 5



To maximum value of unloaded condition normalized representation of absolute fluid velocity

Fig. 6



Distribution of flow velocity along chaffer at fluidized material layer. Top: Simulation. Bottom: Measured data by Freye [1]

Fig. 7

Measuring equipment to validate the numerical models

determined by a parameter study based on the comparison between measured data and simulation results of velocity distribution. With regard to a 3-dimensional simulation of the entire cleaning shoe at reasonable effort, there are no alternatives for modeling the sieves as porous layers. Due to the selected parameters the curve fits very well to the experiment, especially in the middle of the chaffer area (**Figure 4**). The local minimum in the rear part of the curves is caused by connection of chaffer and chaffer extension, which can‘t be passed by the flow.

The calculation with geometrically represented louvers shows a variation of the velocity distribution concerning amplitude and position of the maxima compared to the experiment. This is due to the transition from the real, three-dimensional geometry to a two-dimensional longitudinal section. Friction- and inertia-related losses caused by the lateral inlet of the fan and the subsequent deflection of the air stream in the real geometry are neglected in the two-dimensional approach. Hence the volume flow rate is calculated higher. The shift of the maxima is also due to the neglect of the third dimension. The finger-like design of the louvers in reality leads to the initiation of three-dimensional shear flows and vortex structures, whereby more kinetic energy is dissipated compared to the two-dimensional simulation. The higher flow resistance in reality leads to homogenization of the velocity distribution, as shown in **Figure 4** based on measured values. A detailed investigation of the flow in the gap between the louvers, which was part of the project, has confirmed the statements above.

The results of the simulation under loaded conditions show a flow field, which differs significantly from that of the unloaded conditions (see **Figure 5** and **6**).

Due to the flow resistance of the material layer, there is a substantial equalization of the flow velocity distribution along the chaffer, unfortunately with higher values at the end of it. This condition has a negative influence on the performance of the cleaning shoe and reflects the practical experience and data from the literature [1–6] (**Figure 6**). The modeling of the flow resistance of the material layer affects the simulation results mainly at the rear part of the chaffer. Here, the fluid velocity is significantly greater when using an UDF, due to the exceeding of the virtual fluidization point along with the constant flow resistance, which is lower in contrast to porous layers.

A fluid velocity, which is decreasing towards the end of the chaffer could affect the performance of the cleaning shoe positive, according to [3]. Based on the results of the simulation, it is now necessary to make design changes to improve air distribution and to assess their effect by using the presented models as well as to confirm them experimentally.

Validation

The validation of the numerical model is done by experimental studies. Therefore a measuring device with five anemometers is used (**Figure 7**), which is guided along the chaffer and measures the fluid velocity at defined points on the entire screen surface. In order to make this two-dimensional profile comparable to the simulation results, a mean value is calculated over the chaffer width. The presented measuring device is only suitable for measurements under unloaded conditions. It is further planned to use non-invasive measurement method to capture the flow profile under loaded conditions, so that the models for the flow resistance of the material layer can be evaluated.

Conclusions

The studies confirm the applicability of the computational fluid dynamics as a development tool for the present problem. Due to the simplification of the solution domain to a two-dimensional longitudinal section and the use of a model for the flow resistance of the material layer, the calculation time is acceptable for practical purposes. With regard to a three-dimensional simulation of the cleaning shoe, a possibility for the abstraction of chaffer and sieve is given. Under loaded conditions, the simulation results show the unfavorable increasing fluid velocity curve along chaffer. In future work, computational fluid dynamics along with experimental validation will be driven towards being accurate tools to predict the effect of design modifications to improve the flow profile.

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