Weigler, Fabian; Franke, Georg; Scaar, Holger and Jochen Mellmann

Experiments on particle flow in a newly developed mixed-flow dryer geometry

To preserve large mass flows of grain for long term storage, mixed-flow dryers (MFD) are increasingly used worldwide. Design elements which are unfavorably constructed or arranged can cause broad residence time distributions. Hence, locally different drying conditions occur followed by inhomogeneous drying. As a result, the specific energy consumption increases accompanied by economic and quality losses. With the objective of saving product quality and increasing energy efficiency a new dryer geometry was developed. To compare and evaluate the new design with the traditional geometry regarding solids transport, a series of semi-technical particle flow experiments were performed using wheat as bed material and colored tracer particles

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Mixed-flow grain dryer, solids transport, tracer particles, dryer development

Abstract
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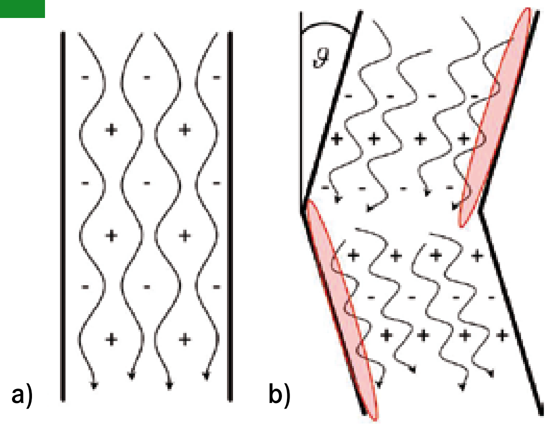
A mixed-flow dryer consists of a vertical drying shaft, at the top of which the cleaned, free-flowing grain is charged. Roof shaped inserts are arranged uniformly over the entire height distributing the drying air. The moist material flows down vertically due to gravity. At the bottom of the dryer, a discharge device is installed to control the residence time of the product in the dryer. The uniformity of drying is determined by shape, size, number and arrangement of the air ducts for inlet and exit air. Besides the airflow, this installation will significantly influence the motion behavior of the bulk material. Although the mixed-flow dryer is state of the art, the apparatus design remained almost unchanged over the past decades and has not been subjected to any systematic procedural analysis.

Early studies on the influence of different air duct geometries on the particle flow have been carried out by Maltry [1] and Klinger [2] using colored grains. However, their conclusions are just based on qualitative analyses. Chaabouni et al. [3] examined the bulk movement in MFD based on a residence time analysis with colored tracer particles. As they could demonstrate experimentally for the first time, the particles in the center of the dryer flow faster as particles close to the wall. The majority of previous research papers focused on methods to increase the dryer performance and to save product quality, e.g. by improving dryer control [4-6]. Using analytical and numerical models, different authors tried to describe the drying process in mixed-flow dryers [7, 8]. In order to investigate the bulk motion and thus the distributions of the particle velocity and the residence time in a MFD precisely, Iroba et al. [9] and Weigler et al. [10] developed two-dimensional models based on the Discrete Element Method (DEM). Using the discrete calculations particle trajectories in a mixed-flow dryer were determined. The model predictions confirmed the experimental results obtained from particle flow measurements and confirmed that particles in the center of the dryer flow faster than those in the near wall regions. This phenomenon is known as core flow effect causing inhomogeneous particle flow. As a consequence, non-uniform drying occurs which is characterized by strong fluctuations of the grain moisture distribution over the cross section at the dryer outlet [11]. Particles having a higher velocity and lower residence time are under-dried, while particles with a lower velocity and, thus, a high residence time are over-dried. Therefore, it is necessary to optimize the geometry of the mixed-flow dryer apparatus and to improve the drying process. In this way, drying costs and quality losses due to over-drying can be reduced and the formation of mold and toxins in storage due to over-drying can be avoided.

Newly developed geometry

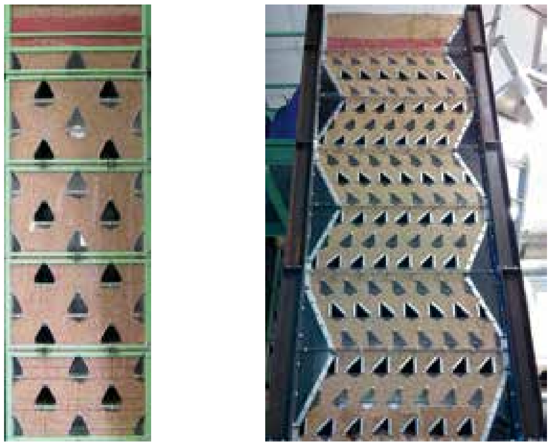
In the drying group of the Leibniz Institute for Agricultural Engineering Potsdam-Bornim (ATB), a new dryer geometry for the MFD [12] was developed (**Figure 1**, b and **Figure 2**, b). The new geometry consists of a vertically arranged drying shaft

Fig. 1



Schematic of the particle flow in a mixed-flow dryer: a) traditional design, b) new developed geometry. The symbols (+) and (-) denote inlet and outlet air ducts, respectively.

Fig. 2



Test dryer with a) traditional design and b) new design (Photo: ATB)

with inclined walls and variable replaceable air ducts. The side walls of a dryer section are inclined to the vertical by a certain angle ϑ. This angle corresponds to the angle of inclination of the diagonals axes running through the centers of the roofs. The direction of wall inclination changes after each dryer section. Therefore, the direction of the particle flow paths varies from section to section. The particle trajectories are parallel to the diagonal rows of ducts, resulting in an alternating flow around hot inlet and cold air exit air ducts. This increases drying uniformity. The complementary angle of ϑ is greater than the angle of repose of most bulk materials, thereby, avoiding bridge formation at the side walls. In addition, the new apparatus design includes a multi-stage product cross-mixing. This is attained by lateral displacement of the air duct rows at the interfaces between the sections (**Figure 2**, b). The multi-stage product mixing has multiple advantages: the drying potential of the air is by far better utilized, strains of moist particles are resolved, the drying conditions are homogenized and, hence, the drying efficiency is increased.

With this arrangement, a systematic generation of regions with low particle velocity near the dryer walls is possible since the inclination increases the wall friction effect. If air ducts are removed in addition, regions with low air velocity occur near the wall. In **Figure 1**, b regions with low particle and air velocities are highlighted in red. By adjusting particle and air velocities in the near-wall regions and in the center of the dryer, drying uniformity and particle moisture distribution are homogenized over the dryer cross section.

Experimental Investigation

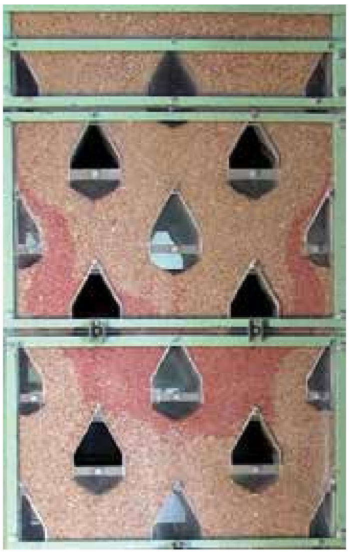
The research on the development of the new dryer geometry is divided into three parts:

- particle flow
- air flow
- drying

In the first two experimental series, the compartment processes of particle and air flow are examined as a start. Based on the first experimental results improvements of the new design have already been made. The third part comprises the „real“ drying process where all the compartment processes are coupled. Only on the basis of practical drying experiments, the effects of design elements can be proved and actually evaluated. Wheat was selected as bed material being as the major cereal in Germany. As compared to corn, the particle size of wheat is small enough to provide flowability in the down-scale semi-technical dryer. Further development of the new dryer geometry and the market launch is planned in a succsession project. The results will be transferred to a large-scale demonstrator by scaling-up in the measure of 1:5. The industrial plant shall be used for drying of various products such as wheat, rye, barley, maize, sunflower and other free-flowing grain crops. These products significantly differ from each other in terms of particle shape and size. The particle flow experiments were performed at, both, the traditional and the newly developed geometry on pilot plant scale (**Figure 2**).

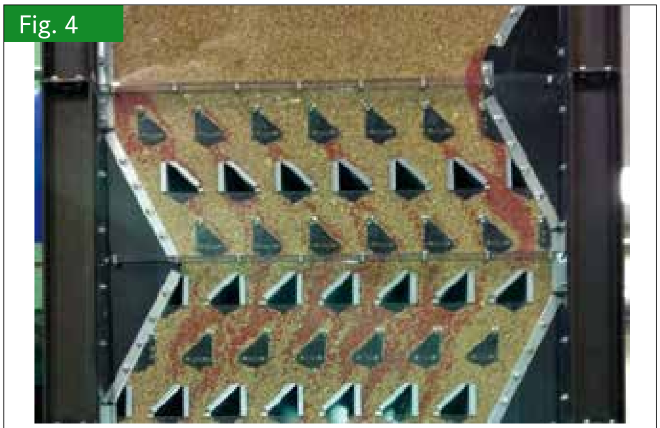
Both dryers have a clear cross section of 0.6 x 0.4 m (without inlets). To visualize the particle flow the test dryers are equipped with a wall made of acrylic glass. The dryer with the traditional geometry (**Figure 2**, a) consists of a vertical shaft with a height of approximately 2 meters, a width of 0.6 m and a depth of 0.4 m. Roof shaped ducts for inlet and exit air are arranged uniformly in the dryer shaft. The ducts have a width of 0.1 m and a height of 0.13 m. The duct angle is 30° (angle of inclination to the vertical). The horizontal duct interspace is 0.2 m. The rows are dislocated by a distance of a half duct. The air ducts are opened at the bottom so as to allow the air to flow into the bed or to escape from the bed. The dryer with the new geometry (**Figure 2**, b) consists of a vertically arranged drying chamber with inclined walls and is divided into six sections where the direction of inclination changes from section to section. The dryer shaft has a height of about 2 m, a width of 0.6 m and a depth of 0.4 m. The trapezoid-shaped ducts with a width of 0.05 m and a height of 0.055 m are arranged in horizontal rows over the dryer shaft. The duct angle is 45°. A dryer sec-

Fig. 3



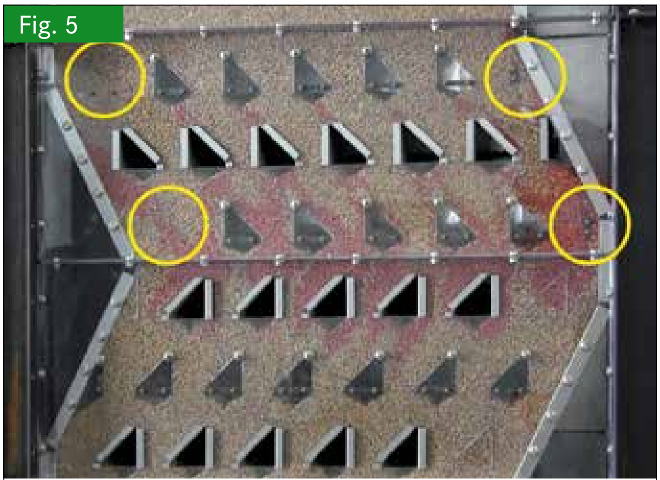
Partikelströmungsprofil gefärbter Weizenkörner in der herkömmlichen Apparategeometrie (Foto: ATB)
Fig. 3: Particle flow profile of the colored wheat particles in the test dryer with traditional design

Fig. 4



Particle flow profile of colored wheat particles in the test dryer with new design and maximum number of air ducts (Photo: ATB)

Fig. 5



Particle flow profile in the new designed dryer geometry with optimized number of air ducts (Photo: ATB)

tion consists of 3 rows of air ducts. Each row includes 6 full and one half air duct. The horizontal roof distance is 0.04 m. The sections are identical in each case and mirrored alternately about the vertical axis. The experimental pilot scale dryers are provided with a pneumatically operated discharge, which is based on the principle of the rotary valve and ensures a constant volumetric discharge. With this discharge system, a uniform mass flow over the outlet cross section is guaranteed. In order to determine the influence of the discharge device, flow experiments were conducted without discharge system. The results showed a similar flow profile within the dryer which, however, was more pronounced because of the higher particle velocities as in the experiments with discharge system. These results will not be discussed further in this work. To visualize the particle motion, a layer of colored wheat grains 150 mm in height (**Figure 2**) was introduced into the bed. The reproducibility of the experiments was confirmed by repeating the experiments. This was only possible by using stock wheat of consistent quality. The moisture content was 15% w.b. and the bulk density ρ_s = 780 kg/m³. Another reason for selecting stock wheat was the low storage capacity of farm-fresh grain at our institute.

Results

The experiments show the qualitative comparison of the measured particle flow profiles of the colored particles. **Figure 3** depicts the particle flow profile of bulk wheat in the traditional dryer geometry after 4 seconds of continuous flow (discharge open) [13]. It is clearly visible that the colored particle layer has a pronounced flow profile due to the influence of the wall. The particle stream through the center of the dryer has a higher velocity than the vertical particle stream close to the wall. The long tails near the walls show the influence of the dryer wall and half the air ducts. By observing the color profiles inside the air ducts, a similar particle flow profile was determined over the depth of the dryer, which is caused by the delay of the particle motion at the front and back walls. The influence of the walls particularly increased in the corners of the cross sectional area. The observed flow behavior is analog to the core flow in a silo.

The first experiments on the new dryer geometry were performed with the maximum possible number of air ducts (six full air ducts and one half air duct per row). **Figure 4** illustrates the particle flow profile of the colored particle layer in the newly developed dryer geometry after 4 seconds of continuous flow. In the center of the dryer, a homogeneous flow profile of particles can be seen. At the same time, the particles near the side walls were significantly retarded in flow which is due to the small distance between the ducts near the wall and the inclined dryer wall. To reduce the high tailback of the particle flow near the side walls, two full air ducts near the wall and two opposite half air ducts were removed per section (**Figure 5**). The positions of the extracted air ducts are marked in yellow in the image. Thus, the particle flow was significantly accelerated near the wall. The photo shows the colored grain layer after 4 seconds of continuous discharge. In the center of the dryer, a homogeneous particle flow was observed which was slightly delayed in the near-wall regions. The profiling over the dryer depth could not be prevented but reduced at least. The change of the wall inclination from section to section associated with a change of the particle flow direction leads to an increased back-mixing in the dryer. Thereby, the average residence time is increased indeed, however, the drying is homogenized. In addition, by the removal of the air ducts regions with lower air flow are created near the walls where streaks of grain flow with low particle velocity. Using this effect, the drying rate can be influenced in order to avoid over-drying in the near-wall region.

Conclusions

With the newly developed geometry, it is possible to locally adjust both particle and air velocities so as to counteract over-drying near the walls. The multi-stage product cross-mixing increases the drying efficiency. With a homogenized drying, energy can be saved and also the product quality can be improved. The positive effects of the new dryer geometry on energy demand and product quality could not be verified in this experimental investigation so far. This verification can be performed by drying experiments on the new dryer geometry, carried out in a succession project.

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Authors

Dr.-Ing. Fabian Weigler is a researcher, **Dipl.-Ing. (FH) Holger Scaar** and **Dipl.-Ing. (FH) Georg Franke** are test engineers and **Dr.-Ing. Jochen Mellmann** is head of the working group drying at the Leibniz Institute for Agricultural Engineering Potsdam-Bornim (ATB), Department postharvest technology, Max-Eyth-Allee 100, 14469 Potsdam, Germany, e-mail: fweigler@atb-potsdam.de

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