LANDTECHNIK 73(6), 2018, 204–213
DOI:10.15150/lt.2018.3198

LANDTECHNIK
AGRICULTURAL ENGINEERING

Process optimization of mixed flow dryers for drying agricultural crops

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Mixed flow dryers (MFD) are usually applied when large quantities of cereal and maize grain and soybeans need to be made fit for storage. Although the process of convective drying has already been extensively studied and is state of the art in thermal cereal preservation, there are still inconsistencies in the description of the overall process and, above all, a great potential for optimisation in the design of the apparatus used for drying. Through process analysis and development of the drying apparatus, considerable progress can be achieved in grain drying for both process and product quality. For this, it is necessary to increase knowledge through investigations of the mixed flow dryer and of the sub-processes of particle movement, air flow, and heat and mass transfer. Based on experimental and numerical investigations of these processes by means of discrete particle modelling and numerical flow simulation, various innovative dryer configurations have been developed. These configurations lead to a homogenisation of the drying conditions, to a better utilisation of the drying potential of the air and thus to improved drying efficiency.

Keywords
Grain drying, mixed flow dryer, DEM, CFD, dryer development

Drying grain after harvest is absolutely necessary in order to achieve a better product for storage, handling and further processing (Brooker et al. 1992, Das et al. 2003). The drying process depends on product quantity, moisture content at harvest and product quality required for particular applications. The requirements regarding product quality are decisive for the drying parameters such as grain temperature and, with that, establish often the choice of suitable drying system.

Continuous dryers are the most-used type of grain dryers worldwide. A special version of this concept – the mixed flow dryer (MFD) – is increasingly used where product throughput is large and moisture content high. The heated drying air is conducted into the vertically flowing grain mass via a system of horizontally arranged roofed-shaped air ducts. The configuration of these ducts allows vertical particle streams travel through, one after the other, direct flow, counter flow and cross flow areas in the entire dryer tower. Even small alterations in the form and configuration of the air ducts substantially influence homogeneity of the drying and, with that, process quality. Unsuitable dryer designs can thus cause a wide residence time distribution and uneven drying that can lead to overdrying or underdrying of the grain that in turn can cause quality loss and increased energy consumption. As demonstrated by Liu (1993), there are significant differences in retention time of individual grains and their temperature process. These lead to a greater spread of grain moisture and grain temperature at the dryer outlet.

The drying process in the mixed flow dryer is extremely complex in that the grain and the drying air move simultaneously parallel, in opposing direction and in cross direction through the dryer

received 30 April 2018 | accepted 1 November 2018 | published 28 December 2018

tower (Pabis et al. 1998). This is possibly one reason why only few scientific investigations (Cenkowski et al. 1990, Giner et al. 1998) are available concerning the sub-processes of air flow, particle movement and the transmission of heat and mass. So far, no comparable studies have been published on constructional alterations of the dryer and their effect on fuel consumption, grain quality and dryer throughput capacity. Nevertheless, at regular intervals individual theoretical analyses and also practically-oriented trial series from manufacturers appear that, through targeted process optimisation (temperature zones, cascade configuration and geometric alterations), have led to increases in drying efficiency (Mühlbauer 2009, Olesen 1987).

The majority of this work so far has concentrated on the development and optimisation of dryer controls (Courtois et al. 1995, Liu et al. 2003), but also the apparatus geometry. In recent years, the number of scientific projects conducted on MFD increased (Cao et al. 2007, Mellmann et al. 2007, Kocsis et al. 2008, Iroba et al. 2011a, Iroba et al. 2011b, Mellmann et al. 2011, Weigler et al. 2012, Keppler et al. 2012, Oksanen 2017). Because of the complex flow patterns and gas-solids interactions, numerical methods are required in order to model individual processes and the total MFD drying process. Towards improving understanding and forecasts relating to the MFD drying process, Mellmann et al. (2011, 2016) have for the first time investigated the influence of different air duct configurations on grain moisture and grain temperature distributions at the dryer outlet, as well as the association between the varying distribution of particle moisture, airflow, and residence time distribution. Hereto, the particulate bed movement and the drying air flows were experimentally investigated and numerically modelled with the Discrete Element Method (DEM) and Computational Fluid Dynamics (CFD) (Kocsis et al. 2008, Iroba et al 2011a, Iroba et al 2011b, Mellmann et al. 2011, Weigler et al. 2012, Scaar et al. 2016). The distributions of particle moisture and particle temperature were analysed in semi-technical (model scale) drying experiments. The influence of certain design elements on the residence time distribution and the existence of differing particle flow regions were documented (Iroba et al. 2011a). The close association between particle profiles and airflow profiles on the one hand, and grain moisture distribution after drying over the cross section of the apparatus, on the other hand, could be proven (Mellmann et al. 2011, Mellmann et al. 2016).

Through process optimisation of the dryer geometry, the dryer performance can be markedly improved compared to conventional dryers. To increase product and process quality, it is necessary to widen knowledge over this dryer concept and to investigate the individual processes of particle movement, air flow and heat and material transport. The aim is to develop a high-performance dryer through new developments in apparatus geometry, as well as geometric adaptation of fittings.

Investigations of the actual state

Grain does not dry evenly in mixed flow dryers, i.e. there exist significant moisture and temperature gradients over the entire dyer cross section because of inhomogeneous particle flows (core flow) and process air flows (dead zones). Even if the degree of inhomogeneity during the aftercooling procedure diminishes and, independently of this, the average moisture content reaches the desired level for storage, there still remains a substantial variance in moisture distribution among the grains at the dryer outlet. These particle moisture content variances can be up to 5% by weight over the total cross section (Mellmann et al. 2011).

To identify the inhomogeneous product moisture distribution during the drying process, the geometry of a MFD in semi-technical scale was experimentally and numerically analysed. The dryer

(Figure 1) comprised a vertical tower around 2 m in height and 0.6 m in width. Roof-shaped ducts for inlet and outlet air were uniformly arranged within the dryer tower. Horizontal rows with half air ducts on the side walls alternated with rows without half air ducts. The dryer had a cross section area of 600 x 400 mm in the horizontal. To investigate particle movement, the dryer was fitted with a front wall of acrylic glass. Air inlet duct hoods, as well as the hoods on the exhaust air outlet ducts, could be easily removed for observation of particle movement.

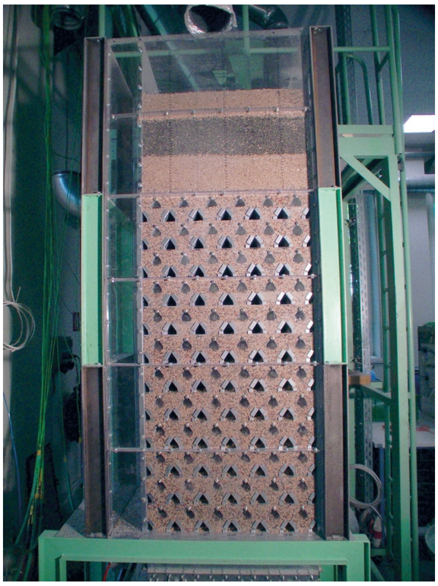

Figure 1: The geometry of the experimental dryer without air inlet and outlet duct hoods for process analysis of particle flow, airflow and the drying process (© F. Weigler)

Bulk grain movement

Figure 2 shows the experimental and numerical flow profiles of the bulk material as recorded in the experimental dryer. Visible are two movement zones: a relatively broad core flow zone in the middle and flow zones in the vicinity of the side walls, with a marked velocity distribution.

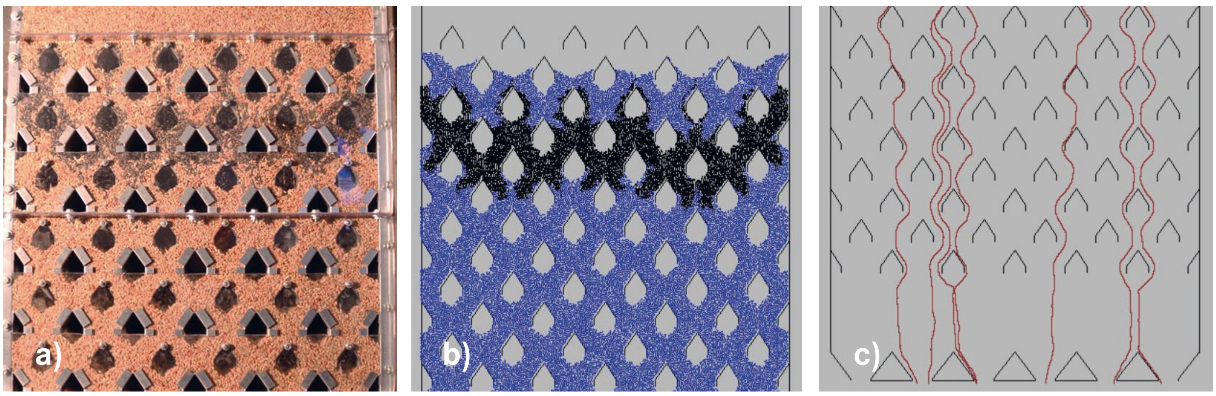

Figure 2: Particle movement in the test dryer: (a) experimental, (b) numerical and (c) particle trajectories

As shown in Figures 2a and b, the core flow zone indicates a homogeneous flow profile over a wide area. The flow profile is caused by frictional resistance effects between the particles and the dryer tower sides or the air ducts. As shown by the simulation of the particle trajectories (Figure 2c), there exist particle streams without any lateral mixing between the roofs over the entire dryer tower height. The investigations on particulate bed movements also showed, however, a definite flow profile over the depth of the dryer. Through the possibility of being able to see into the air ducts, the particle movements beneath the ducts in the inside of the dryer tower could also be investigated. It was observed that tracer particles within the dryer tower moved much more quickly than those on the transparent plexiglass front wall and back wall. This meant that in the MFD a flow profile developed over the entire cross section, a profile comparable with the core flow in a silo.

Drying air flow

Numerical simulations of the drying air flow were carried out in a filled dryer in order to investigate the air flow distributions for different air duct configurations (Weigler et al. 2012, Scaar et al. 2016). Hereby, it was assumed that during the "stand period" the particle movement was not influenced by the air flow. The "stand period" is defined as the rest phase between two discharge procedures and the period of time required for opening and closing the grain discharge device – the socalled discharge time (Mellmann et al. 2011b). Figure 3 shows the horizontal configuration by which rows of inlet and outlet ducts are arranged alternating under one another. The air ducts are signified by '+' for inlet ducts and '-' for outlet ducts.

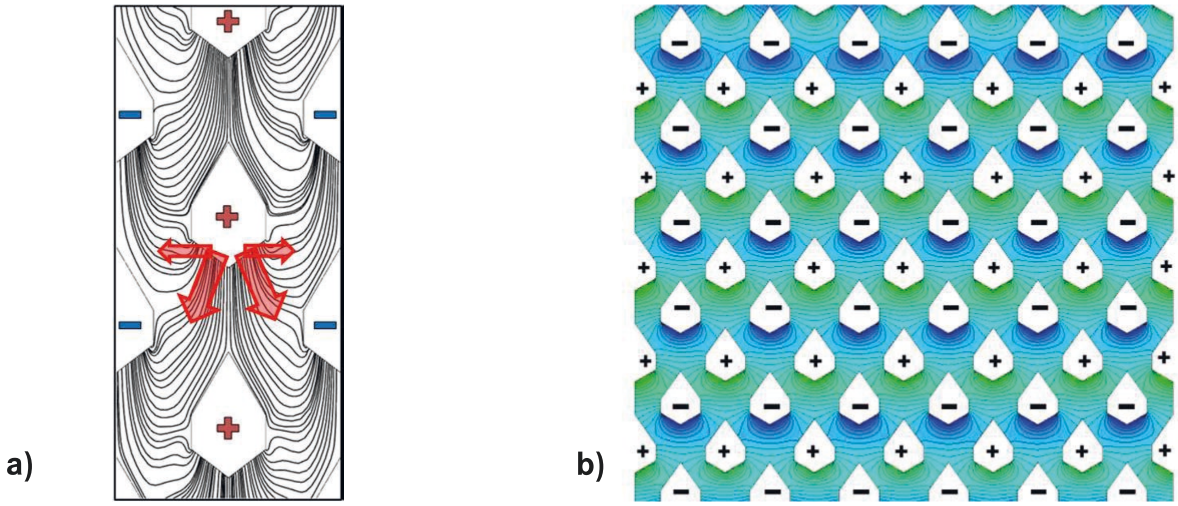

Figure 3: Simulated air flow distribution in the experimental dryer with horizontal configuration of the air ducts: (a) flow line presentation and (b) pressure distribution (static particulate bed; air flow rate of 465 m^3/h), (+) inlet air and (-) outlet air ducts.

As shown by the numerical results, the air flow distribution in the horizontal configuration is homogeneous (almost constant colour profile). As Cenkowski et al. (1990) have already proved in experiments on air flow, with the horizontal configuration the inflowing air is not uniformly distributed from an inlet duct to the four adjacent outlet air ducts. The partial air current to the upper outlet air ducts is, however, only minimally lower (40/60) than those to the lower outlet air ducts. This effect could be confirmed through numerical investigations conducted by Weigler et al. (2012) (Figure 3a).

Drying

Differing particle retention times between the dryer tower middle and the side wall areas led to a definite particle moisture distribution at the dryer outlet. This effect increased the more the particle flow and the air flow velocities differed, as observed in cross section. Drying experiments were conducted with farm-fresh wheat at initial moisture content of ~ 15% by weight. Drying period was 90 min with a drying air volume flow of 465 m^3/h and an inlet air temperature of 80 °C. The results of the drying experiment are shown in Figure 4. Shown is the grain moisture content over the dryer cross section as measured in the stationary mode at dryer outlet. The experiments were conducted with the above described dryer geometry (Figure 1). As clearly shown by the graph, the particle moisture fluctuates over the dryer cross section.

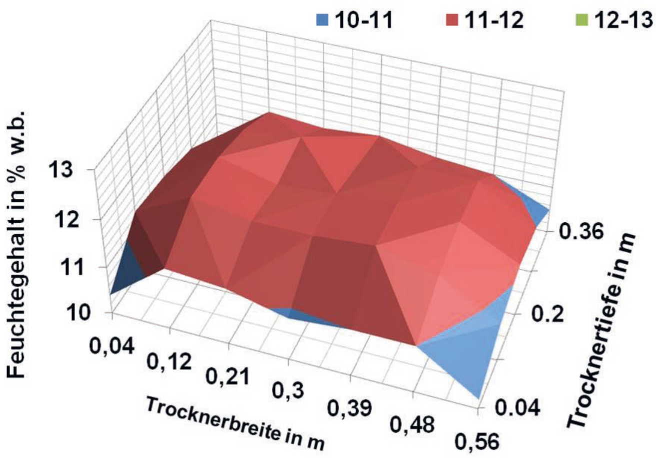

Figure 4: Average moisture content over the dryer cross section at outlet, measured in semi-technical scale, see Figure 1

For the experimental dryer the material moisture content varied between 10 and 13% by weight over the total cross section. As expected, particle moisture near the side walls, and particularly in corners of the tower, is markedly reduced through a longer particle residence time. Hereby, strands of cereal grains could be over- or underdried, as was already described by Giner et al. (1998). The result of this is an uneven moisture content distribution during drying. Even with just a few moisture "nests" with particle moisture content of > 14.5% by weight, the risk of quality loss during subsequent storage increases.

Dryer development

Based on the research results, new dryer constructions were developed and successfully tested by the working group "Drying Technology" of the ATB Potsdam. Development aims are further improvements in exploiting the drying potential of air, to homogenise the drying conditions and, with that, increase drying efficiency. In the following, two examples of new MFD geometries are presented. The new versions are characterised by the following construction features:

- Alteration of the roof-shaped angle in the vicinity of the side walls – influencing bulk material movement
- Adding a row of closed air ducts – influencing air flow currents

Influencing particulate bed movement

As indicated by the investigations on particle movement – experimental as well as numerical – the wall friction exerted substantial influence on particle movement in the MFD (Figure 2a). The results show two flow zones: a central core flow zone and a zone in the vicinity of the side walls. Grains in the middle of the dryer move at higher velocities and leave the tower faster, whereas grains in the vicinity of the side walls have reduced flow velocities due to the friction effects between particles and side walls and/or through air ducts (Iroba et al. 2011a).

A new dryer geometry developed at the ATB Potsdam is based on the classical horizontal air duct configuration whereby in the vertical dryer tower the air inlet and air outlet roofs are horizontally offset. Other than with the classical roof-shaped geometry, where all air ducts are mirror-symmetric in cross section (Figure 5), the new developed roof-form geometry is asymmetric. In each case, these air ducts are fitted in the vicinity of the side walls (Figure 6). The scalene triangle at the peak of the duct cross section is caused through reduction of the roof slope angle α of the roof half facing the side wall. Air ducts with this altered geometry are, however, only arranged along vertical air duct rows near the side wall (Figure 6b). These air ducts accelerate particle flow through reduction of the wall friction angle. The idea behind this is achieving acceleration of particle flow, or slow this flow down, through manipulation of the effective friction angle, and thus achieve a uniform flow profile.

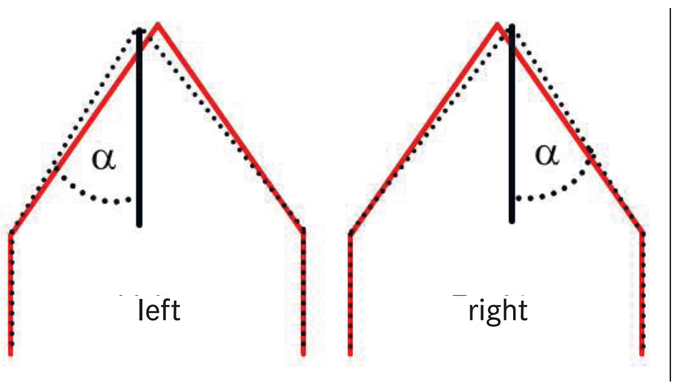

Figure 5: Geometric presentation and qualitative comparison of the original (red line) and the new devel-oped (dotted line) roof geometry

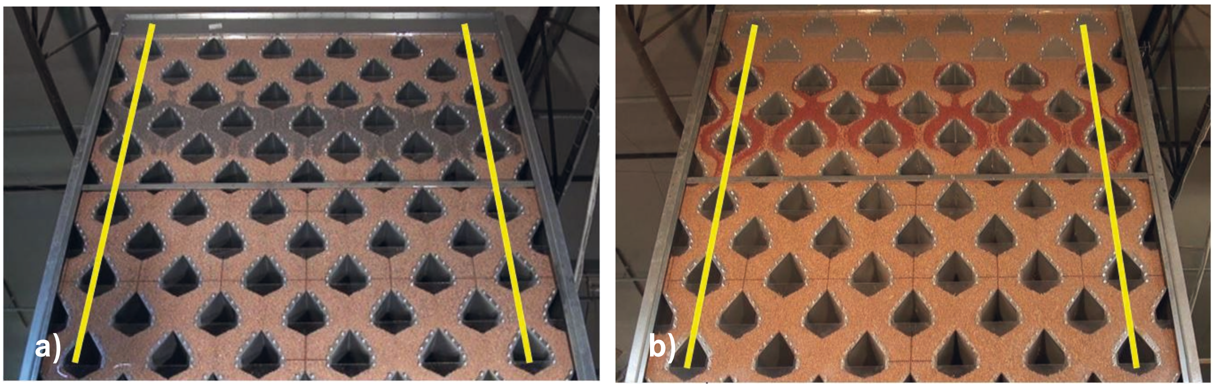

Figure 6: Experimentally measured particle flow profile for (a) conventional air ducts and (b) new developed air ducts (with altered roof angle in the vicinity of sidewalls) (© F. Weigler)

This development has several advantages: The drying potential of the air streaming through the area in the vicinity of the side wall has a much greater beneficial effect because the drying conditions are homogenised and thus drying efficiency increases. With this arrangement, a symmetrical increase of particle velocity in the vicinity of the dryer tower walls is possible because the steeper roof slope reduces the effective friction angle of the grain mass and thus counteracts the side wall friction effect. In Figure 6b, the influence of the newly developed air ducts is visible, for instance, in that the homogeneous core flow zone in the middle of the dryer is extended towards the side walls. This flow pattern was experimentally determined in semi-technical particle flow experiments. Through adapting the particle velocities in the areas in the vicinity of the side walls and in the middle of the dryer, the uniformity of drying and the grain moisture distribution over the entire cross section is homogenised. Energy can be saved through a more homogenous drying, and product quality improves. These dryer designs were successfully scaled-up to industrial dimensions and validated as a practical configuration during harvest 2018 in cooperation with the NEUERO Farm- und Fördertechnik GmbH.

Influencing drying air flows

The investigations of drying air flow streams for horizontal air duct configurations show that the air from one inlet roof (+) flows to the surrounding 4 outlet air ducts (-) (Figure 3a). However, this results in an uneven distribution of the drying air between the two exhaust air ducts above and the two below the inlet air duct. With a conventional air duct configuration in the MFD (Figure 3b), vertical particle strands of moist grains occur due to reduced lateral mixing and the positioning of the inlet and outlet air ducts one above the other (Mellmann et al. 2011). In order to counteract this effect, several manufacturers of dryers have turned alternate drying tower sections around on their respective vertical axes by 180° over the height of the tower (Mellmann et al. 2016) (Figure 6a). The rotation of the sections causes a positive effect on the altered air flow dynamics through the grain from and to the inlet and outlet air ducts. Thereby, individual grain strands are regularly aerated by warm supply air or cold, i.e. relatively moist, outlet air which leads to a more uniform drying effect.

An important disadvantage of this process is, however, the direct sequence of two horizontal rows of inlet air, or outlet air ducts, at the interfaces of the rotated dryer sections. This results in local areas with increased air velocities due to oversupply of inlet air (too many inlet air ducts) and areas with low air velocities (dead zones) where too much air is extracted (too many outlet air ducts) (Figure 6a). As a result, in these areas the flow distribution is inhomogeneous, and the classical distribution of inlet air is interrupted. The drying potential of the inlet air is not fully exploited. In a further configuration of the air ducts, inlet and exhaust air ducts are arranged in a sequentially diagonal pattern. Thereby, it has been demonstrated that the air flow is distributed unequally to the surrounding outlet air roofs (Scaar et al. 2016). This results in the development of areas with low levels of air flow and areas with more intensive air flows. For this reason, the maximum air velocities in the diagonal configuration are higher than in the horizontal configuration. Also, exploitation of the drying potential of inlet air cannot be increased in the diagonal configuration.

Therefore, a new version of the MFD was developed based on the horizontal air duct configuration (Patent Scaar et al. 2015), where each drying section was extended with a row closed of air ducts at the bottom (Figure 7b). Recently Oksanen (2017) suggested a similar design to increase the retention time of the air and thereby better exploit drying potential. In this case, every row of inlet and outlet air ducts was followed by a row of closed ducts.

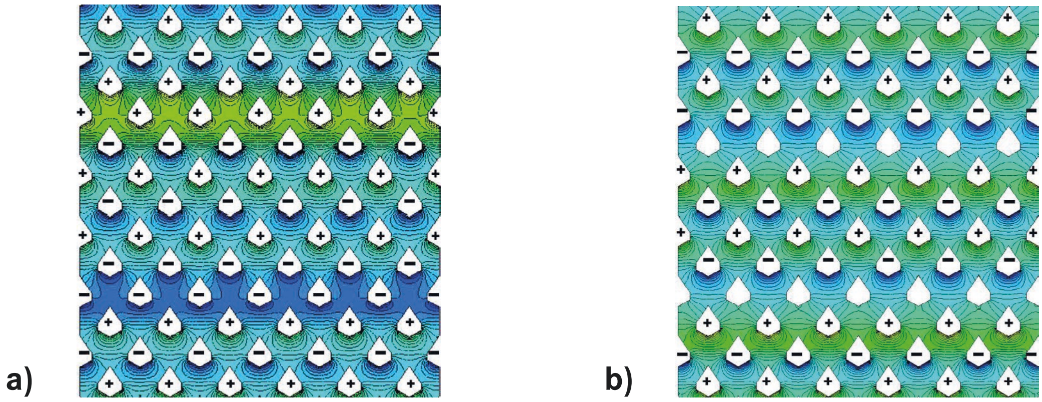

Figure 7: Pressure distribution in the MFD for (a) horizontal configuration of the air ducts with revolved sections and (b) the new design with a row of closed ducts per dryer section simulated with an air flow rate of 465 m^3/h

As can be seen in Figure 7b, an identical drying section comprises in total five rows of air ducts: in each case two rows for inlet air and outlet air and one row with closed ducts. The fitting of a row of closed (no flow) roof rows in every drying section offers various fluid-mechanical and drying advantages:

- The production of a compensation zone at the end of every dryer section,
- Retention of the homogeneous air flow distribution,
- In the majority of cases, quartering of the air flow of every inlet air duct (Figure 3a)

The compensation zone at the end of each dryer section enables a moisture and temperature compensation in the grain bed and, thus, accelerates drying in the next section. The establishment of zones of low air flow (dead zones) is impeded, moisture and temperature strands due to under- or overdrying are avoided. With the new developed configuration, uniform drying conditions for cereal grains of different trajectories are achieved. This was confirmed through semi-technical drying experiments in which grain moisture and temperature distribution were significantly homogenised in comparison to conventional dryer designs. The new design has been transferred to an industrial plant that is currently being tested.

Conclusions

Analysis and optimisation of the MFD dryer design can enable advances in the process and product quality. Based on experimental and numerical investigations on particle flow, air flow patterns and particle drying using DEM and CFD, various innovative MFD dryer configurations have been developed by the working group drying technology of the ATB Potsdam. Two of these configurations are presented in this article. The first results show that, with the new dryer version, drying conditions are homogenised, the formation of grain moisture and temperature strands is reduced, and grain moisture distribution is homogenised after drying. This can potentially save thermal energy, improve product quality and increase operational reliability. Both constructions have been scaled-up to industrial dimensions and are currently being tested in running research projects.

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Acknowledgement

The authors thank the Federal Ministry of Food and Agriculture (BMEL) for the support given within the framework of the German Innovation Partnership Agrar/DIP (Project “InnoTrEnt“, FKZ: 744170/1).