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Investigation of the drying airflow at a newly developed dryer geometry for mixed flow grain dryers

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In honor of Prof. Dr.-Ing. habil. Werner Maltry on the occasion of his 85th birthday

The mixed-flow dryer has been a matter of investigation many times regarding drying efficiency, dryer control, and performance enhancement over the past years. However, there is still considerable demand for optimization in terms of energy efficiency and homogeneity of drying. In order to analyze the specific energy consumption and the homogeneity of the drying process, different thermodynamic process conditions have been investigated for the conventional MFD design using numerical and experimental methods. Based on the results obtained, a novel dryer design has been developed. With this, a considerable increase of efficiency is expected. As the fluid dynamic analysis of the first design draft revealed, further development is required until scaling-up and transfer into practice will be possible. While homogeneous airflow conditions could be demonstrated in the core flow region in the center of the dryer, the configuration must be optimized in the near wall regions.

Keywords
Grain drying, mixed-flow dryer, CFD, airflow measurement, dryer development

In Germany, 90 % of agricultural companies have decided for a drying process for the preservation of crops (Bombien 2013). For the convective drying of large mass flows of grain, mixed flow dryers (MFD) are used worldwide in great quantities in agriculture, agricultural trade companies, and the food industry (Mühlbauer 2009). Research and development have only insufficiently been responding to this trend yet. Hence, the design of mixed flow dryers has remained unchanged for decades. According to Maier and Bakker-Arkema (2002), no optimized design for this drying process with regard to form, size and arrangement of air ducts has yet been developed to reduce product inhomogeneity in the drying process. The process still holds substantial potential for optimization of apparatus design, since by equalization of drying the efficient use of energy and product quality can be clearly improved.

The MFD consists of a vertical shaft, in which roof-like ducts are installed for even distribution of drying air across the entire column. The evenness of drying in mixed flow dryers is mainly determined by arrangement, form and number of air ducts for inlet air and outlet air. In dryer construction, different particle properties of the drying goods (grain, maize, rapeseed, sunflower seed, etc.) must be considered. From process engineering point of view, a product-specific dryer design should always be preferred, in which changing flow properties (particle form, moisture content) during drying could be considered. In agriculture, however, universal dryers have been established for economic reasons. That is why mixed flow dryers are usually employed for a large number of free flowing, granular products. This complicates an optimal dryer design in addition. Difficulties in calculations

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result from the complexity of the drying process: grain and air flow are guided through the dryer shaft in co-current flow, counter current flow, and cross flow, simultaneously (Mühlbauer 2009, Olesen 1982). This is potentially also a reason for the limited availability of scientific research with regard to airflow, particle movement and heat- and mass transfer (Olesen 1982, Maltry 1966, Klinger 1977, Cenkowski et al. 1990). Particularly the airflow in the MFD has remained widely uninvestigated due to its complexity. At the same time, the airflow distribution in the dryer arrangement substantially influences the temperature distribution and consequently the drying process. The majority of scientific research has yet been focussed on the development and optimization of dryer control (McFarlane & Bruce 1991, Courtois et al. 1995). The various opportunities of procedural optimization of processes have remained widely unutilized. Recently, an increasing number of scientific investigations have been published concerning mixed flow dryers (Mellmann et al. 2007, Mellmann et al. 2011, Keppler et al. 2012). Investigations on air flow through agricultural granular goods were already carried out by Matthies (1956). Cenkowski et al. (1990) described the distribution of isobars in a MFD, applying the finite element method, and compared results with experimentally assessed isobar distributions.

The focus of this research is set on the numeric analysis of flow distribution of the drying air in the newly developed mixed flow dryer, after in a previous research the particle movement in this novel apparatus geometry was investigated (Weigler et al. 2014). A numerical model of the MFD based on Computational Fluid Dynamics (CFD) has been developed (Scaar et al. 2016). For experimental flow investigations, suitable methods for the assessment of isobar distribution and the residence time of the drying air in the grain bulk were developed and applied. The CFD model was validated by using the experimental isobar distributions. Afterwards, the impact of the different air duct arrangements of conventional apparatus designs on airflow distribution is investigated and respective advantages and drawbacks are highlighted. The results provide the basis for analysis of the flow distribution in the newly developed dryer geometry by ATB Potsdam (Mellmann et al. 2012). The numeric calculations have been made under isotherm air conditions with the particle flow at rest.

Numerical Model

For fluid-mechanical analysis of the MFD, a mathematical model based on CFD was developed and validated, using differential pressure measurements (Scaar et al. 2016). The developed model was used to calculate the airflow distribution in the shaft dryer for different dryer geometries and air duct arrangements.

The pressure drop in the grain bulk and airflow distribution were simulated using mass, energy and impulse balances under consideration of the bed material characteristics, the dryer geometry, and drying kinetics. For digital reconstruction of the dryer geometry, various apparatus designs were discretised using a finite volume net. Ansys® ICEM software was used for this process. The subsequent analysis of the airflow distribution was carried out with Ansys® CFX software. To calculate the pressure profile in the grain bulk, the pressure drop equation according to Ergun (VDI 2006) was integrated in the equation of momentum conservation.

Experimental Validation

A test station consisting of an air conditioning device and a mixed air dryer was built for model validation using difference pressure measurements (Figure 1, a). The dryer column includes in total 13 air duct rows in horizontal arrangement and a pneumatically operated discharge gate. Each row of air ducts includes 2 full air ducts. From top to bottom, rows of inlet air ducts with 1 full and 2 half air ducts alternate with rows of outlet air ducts consisting of 2 full air ducts.

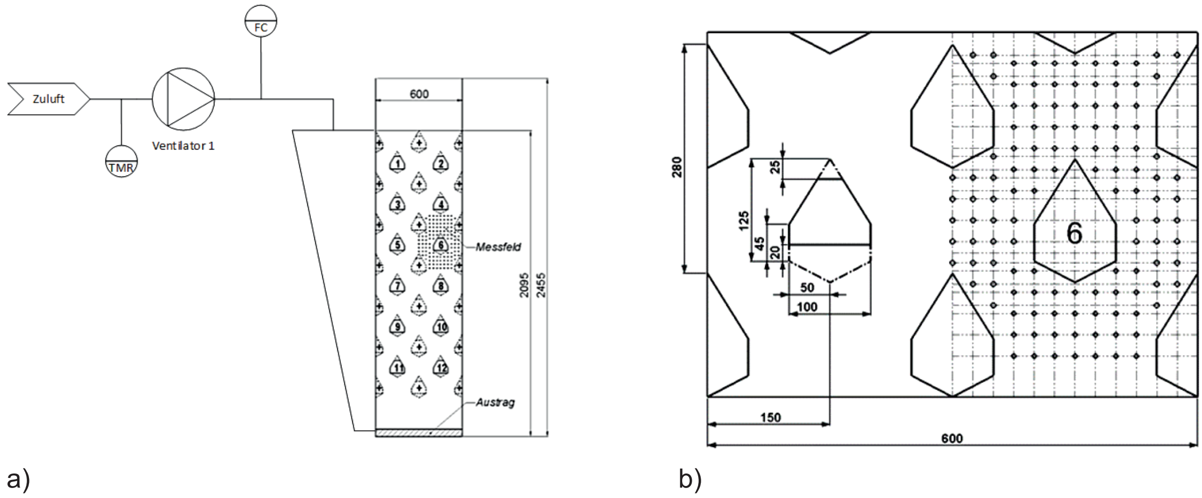


Figure 1: Schematic of (a) the experimental set-up and (b) the isobar measuring field.

With a shaft cross-section of 0.6 m x 0.4 m, the semi-technical dryer was designed matching the cut-out of an industrial dryer. This means, width and depth of the dryer were copied on a 1 : 5 scale. The filling volume of the dryer including supply section is 0.48 m^3. This correlates with a filling mass of 350 kg wheat. The dimensions of the air ducts and the distances between them were not scaled and correspond to those of large scale industrial dryers. Thus, the test dryer matches a cut-out of a real MFD. This has no negative impact on the air flow distribution in the dryer. The similarity of the particle flow also remains unchanged due to using the same bed material (e. g. particle size) and the same air duct dimensions. However, the wall impact is amplified due to the relative closeness of the dryer walls.

The airflow experiments in the dryer were carried out under constant air conditions (20 °C, 65 % r. h.). The airflow rate was set on 465 m^3/h. By calculation, this value results from a mean flow velocity of circa 0.2 m/s in the grain bulk, which is within the range of optimal flow velocities in mixed flow dryers according to Mühlbauer (2009). The granular materials used were dried wheat with a moisture content of 11 %. After filling the dryer, a number of discharges were performed so as to build up the characteristic angle of repose under the air ducts (Figure 1).

To measure the airflow characteristics between the inlet and outlet ducts, the dryer was operated under pressure conditions. For the pressure drop measurements, a measuring field was deployed in about middle height of the dryer between the 5^{th} and 7^{th} row of air ducts (from above). The outlet air box was removed for that. The measuring grid comprised 116 measuring points arranged between the central outlet air duct 6 and the four surrounding inlet air ducts (Figure 1, b). The four surrounding inlet air ducts were each half covered by the measuring grid. This was sufficient for the assessment of the flow distribution, since it is known that in horizontal arrangement a quartering of the air flow rate from one inlet air duct to the four surrounding outlet air ducts is effected (in practical suction mode) (Maltry 1966). Inversely, this also applies for the experimentally realized pressure mode, in which the central outlet air duct 6 was fed by the four surrounding inlet air ducts. The distances between the measuring points were 25 mm horizontal and 26 mm vertical. At each measuring point, a 6 mm hole was drilled in the dryer wall on the outlet air side which can be closed air tight. For the measurements, a measuring rod with a difference pressure sensor was inserted consecutively via the drill holes into the grain bulk and positioned at a depth of 200 mm in the centre of the dryer. The other measuring points (drill holes) remained sealed air tight during measuring.

The measuring probe consisted of a 250 mm stainless steel pipe with 6 mm in diameter. At the tip of the measuring lancet, a gaze with a mesh width of 1mm was fastened to protect the measuring lancet from clogging with grain. At the other end of the measuring lancet, a difference pressure sensor with a measuring range of ± 250 Pa and a precision of ± 1.25 Pa was connected via silicone tube with the pressure side. The vacuum side of the sensor was exposed to ambient pressure. The sampling rate of the measuring sensor was 10 ms. For harmonization of pressure oscillations, difference pressures were mediated over a measuring interval of 120 s. At each measuring point the measurements were repeated three times. A median value was built from these 3 measurements.

To illustrate the measured differential pressures and for model validation, the experimental isobar profile was interpolated using the measurements and compared with the calculated course of isobars (Figure 2). As shown in the graphic, the experimentally assessed isobar profile matches fairly well qualitatively with the numerically calculated profile. Moreover, it becomes clear that the measured isobars are less geometrically structured than the calculated ones. This is caused by the character of the model and mainly based on the assumption of a homogeneous grain bulk with mono-dispersed, spherical particles and an isotropic porosity distribution. In a real grain bulk, however, local porosity differences occur, potentially caused by the distribution of various particle sizes, different orientations of the ellipsoidal grains (e. g. wheat) within the bulk as well as broken grain and impurities.

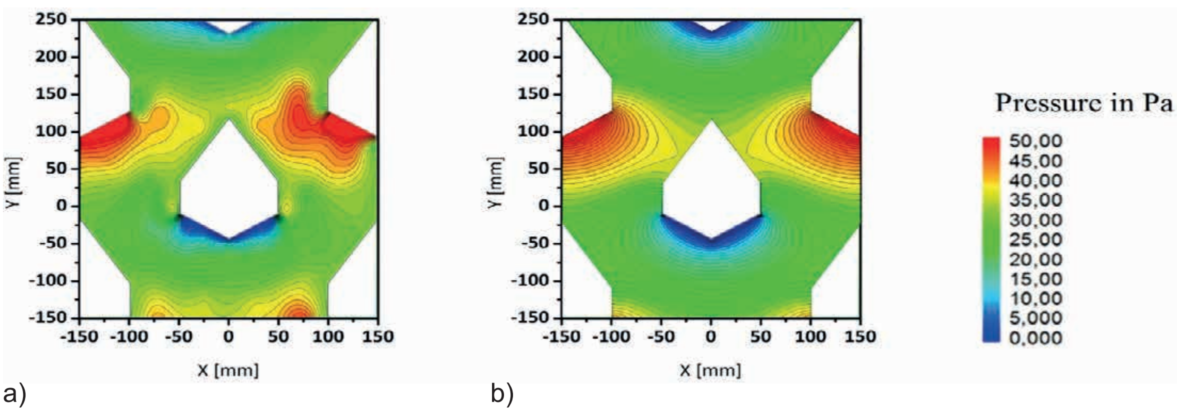


Figure 2: Comparison between (a) measured and (b) predicted isobar profiles over the dryer cross-section, obtained at an airflow rate of 465 m3/h.

A median, relative default of 7.9 % of the model occurred across all 116 measuring points (Scaar et al. 2016). Thereby, this default is just circa 1 % above the median, relative measuring default of all single measurements, hence, very good correlation was achieved.

Results

In the following, the conventional apparatus designs are first investigated numerically to analyse the impact of different air duct arrangements on the flow distribution of the drying air in more detail. Subsequently, these results are compared with the newly developed dryer geometry.

In the horizontal air duct arrangement (Figure 3, a), inlet duct and outlet duct rows are alternating in vertical direction (+ inlet air, - outlet air). A substantial advantage of this dryer geometry lies in the even quartering of the air flow from one inlet air duct to the four surrounding outlet ducts (Weigler et al. 2012) (Figure 2). Considering the flow profile of the grain flow over the dryer cross section on the other hand, it is characterized by a pronounced velocity profile (Mellmann et al. 2012, Weigler et al. 2014). This results in substantial differences in the residence time, consequently causing over-drying of particles at the dryer walls as well as under-drying of particles in the core flow in the centre of the dryer. Due to the low cross-mixing in shaft dryers, vertical strains of moist particles are formed in the grain flow through the stacked inlet air and outlet air ducts, respectively (Mellmann et al. 2011).

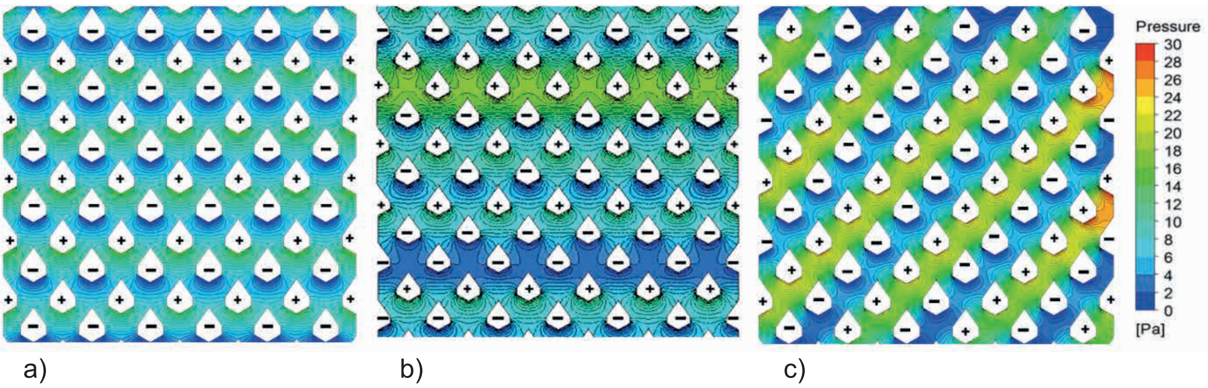


Figure 3: Pressure distribution in the mixed-flow dryer for (a) horizontal air duct arrangement, (b) horizontal air duct arrangement with turned sections, and (c) diagonal air duct arrangement, simulated at an airflow rate of 465 m^3/h.

To counter this effect, the turning of dryer sections in horizontal air duct arrangement (Figure 3, b) is a well proven method in modern mixed flow dryers. For it, identically designed dryer sections are turned around their vertical axis by 180° alternately across the entire length of the dryer. This rotation of sections leads to a change in the vertical flow pattern around inlet and outlet ducts. Thereby, single streaks of grain are periodically flown through by hot inlet air or cold and relatively humid outlet air, respectively, resulting in a more even drying. A substantial drawback resulting from the turning of dryer section is the direct sequence of two horizontal rows of inlet or outlet air ducts, respectively, at the interface between the dryer sections. Thus, local regions of increased air velocities are formed due to inlet air excess (too many inlet air ducts) or regions of low air velocities, respectively, in which air is removed in excess (too many outlet air ducts) (Figure 3, b). In these regions, the flow distribution consequently becomes inhomogeneous and the classical quartering of inlet air is interrupted. The drying potential of the inlet air is not optimally utilized.

Therefore, a special design of mixed flow dryers uses the diagonal air duct arrangement (Figure 3, c). In this arrangement, rows of inlet and outlet air ducts alternate in diagonal direction, so that each streak of grain is alternately exposed to inlet air and outlet air, respectively. This air duct arrangement, however, causes a disadvantageous airflow distribution in the grain bulk. The inlet air from one inlet duct in this arrangement is only distributed to two (instead of four) adjacent outlet ducts (Weigler et al. 2012). Consequently, regions of higher and lower air velocity occur (dead zones) in the airflow through the grain bulk (Figure 3, c).

Based on extensive previous investigations and experience, an innovative design for the mixed flow dryer was developed by the drying group of ATB Potsdam (Mellmann et al. 2012). It consists of a vertically arranged dryer shaft with walls inclined by the angle Θ (Figure 4), with the direction of inclination alternating from section to section. The test arrangement comprises of 6 sections with a height of about 2 m as well as an overall width of 0.74 m at a useful width of 0.6 m and a depth of 0.4 m (Weigler et al. 2014). The air ducts have an asymmetrical, triangular form and are arranged in horizontal rows across the dryer. By the asymmetrical form of the air ducts, they act like vanes thereby supporting the intended guidance of the particle flow in the direction of inclination of the sections. One section consists of 3 air duct rows. Each row comprises 6 full air ducts and one half duct. The sections are alternately turned by 180° around their vertical axis. The advantage of such dryer design lies in the continuously changing exposure of single strains of the granular flow to inlet and outlet air while remaining the horizontal air duct arrangement and the quartering of the inlet air. In addition to that, a product flow mixing (or division) occurs after each drying zone, which is achieved by a respective arrangement of the sections relative to each other (Figure 4). This multi-stage product mixing results in a clear homogenization of the drying.

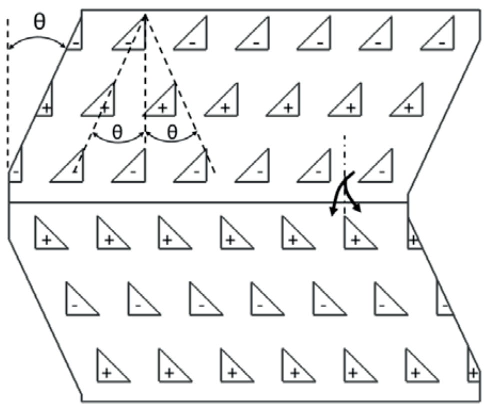
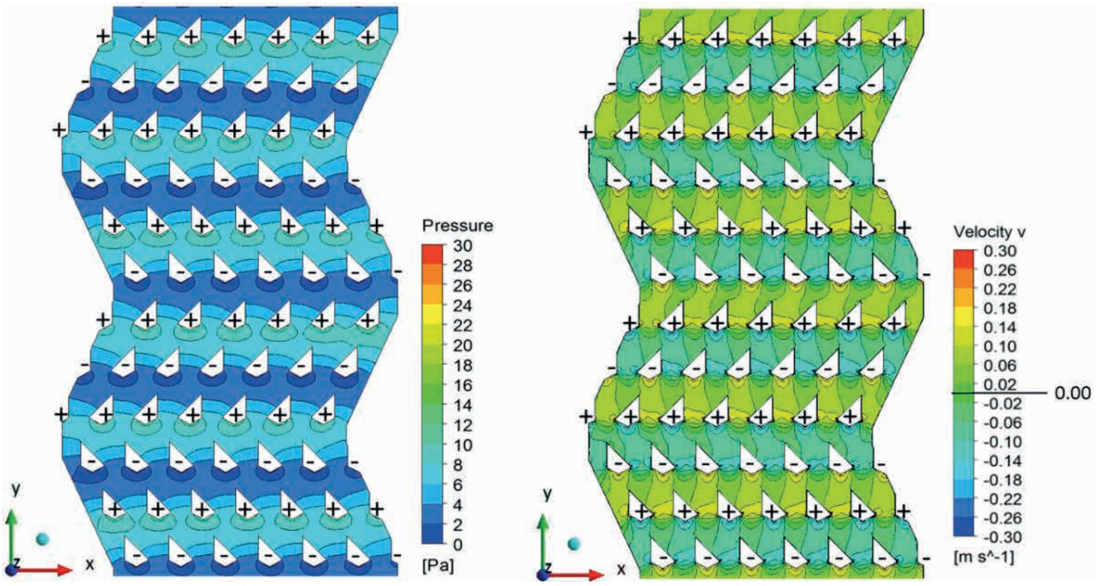


Figure 4: New dryer geometry developed at ATB Potsdam (Mellmann et al. 2012).

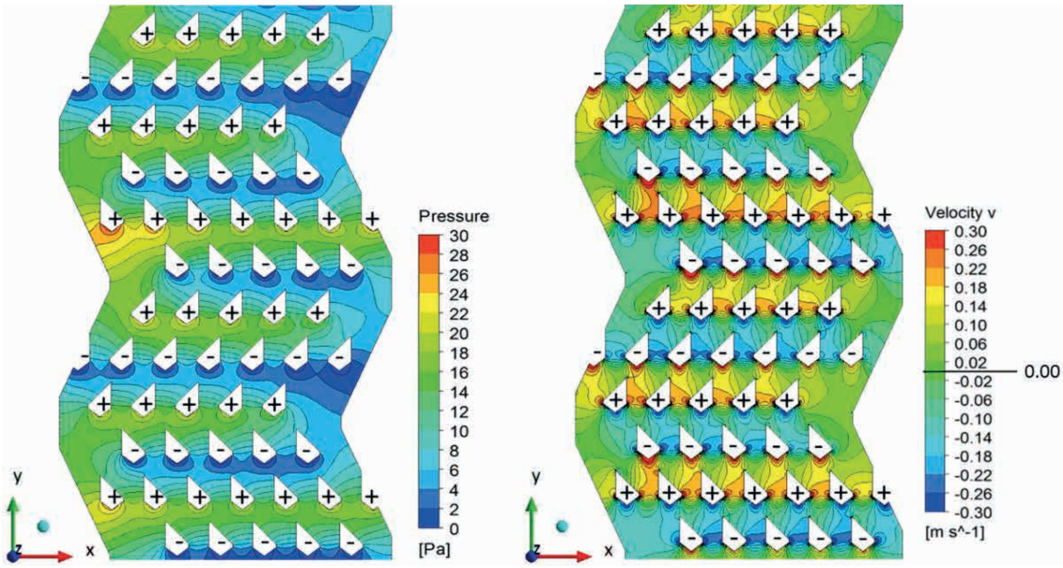
The pressure and velocity distributions illustrated in Figure 5 across the dryer width show that the new design has a positive impact on the airflow distribution. The isobar profile as well as the velocity distribution displays a very homogeneous flow pattern across the overall dryer height. As clearly shown in the illustration of the vertical component of air velocity in Figure 5 (b) regions of co-current flow and counter-current flow are formed between the rows of air ducts. Note that the vertical component of air velocity in direction of the y-axis (upwards) is defined positive. This means that in case of counter-current flow the air velocity adapts positive values and in co-current flow negative values, respectively. This result confirms the quartering of the air flow achieved in this air duct arrangement. The grain flow in the near wall regions, however, is retarded due to the inclined side walls. This effect has been confirmed by flow tests with wheat conducted in the dryer geometry as shown in Figure 4 and 5 (Weigler et al. 2014).



a) b)

Figure 5: (a) Pressure distribution and (b) airflow velocity distribution (vertical component) in the novel dryer design, predicted at an airflow rate of 465 m^3/h.

Since this would have led to over-drying in the near-wall regions of the dryer, this design draft was modified already prior to the tests (drying). Therefore, two full and two half air ducts near the dryer walls were removed per dryer section (Figure 6). This modification resulted in an acceleration of the grain flow at the side walls. An uneven distribution of the process air flow in the near wall areas, however, also resulted from that (Figure 6a and 6b). The “asymmetrical“ removal of two full inlet air ducts on the right and two full outlet air ducts on the left per double section caused a local air excess on the left (increased pressure - yellow/red) and a lack of air on the right (low pressure - blue), respectively (Figure 6a). While even flow conditions occur in the core flow region in the centre of the dryer (Figure 6b), the dryer geometry in the near wall regions requires optimization. Further development is carried out on the new dryer construction in a current research project.



a) b)

Figure 6: (a) Pressure distribution and (b) airflow velocity distribution (vertical component) in the novel dryer design with modified air duct arrangement, predicted at an airflow rate of 465 m^3/h.

Conclusions

The newly developed dryer geometry improves the exploitation of the drying potential of the inlet air by means of a continuous change in the particle flow around inlet and outlet air duct rows, respectively, a more even flow of the granular material due to maintaining the horizontal air duct arrangement with optimized quartering of inlet air, and due to the multi-stage product flow mixing. The newly developed dryer geometry was analysed using the established fluid flow model.

Air ducts at the side walls were removed to improve the particle movement and to reduce the slowing effect of the inclined walls. The fluid mechanical investigation of this modified, new dryer geometry shows, however, that the removal of single air ducts has a negative impact on the process air distribution at the side walls. Further optimization of the newly developed dryer geometry is therefore required in order to attain an improved adaptation of particle- and air flow velocities in the near wall regions. By means of such fluid mechanical research and simulations, it is possible to develop new processes as well as to assess and optimize already established conventional systems from process engineering point of view.

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