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Controlling air flow in recirculating mixed flow batch dryer with double bed mode

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A B S T R A C T

Mixed flow dryers (MFD) are one type of devices used to dry grain after harvesting in farms. The moisture is removed from the grain by air convection through the grain bed using air ducts installed in the bed. In the normal mixed flow dryer, every other row of air ducts acts as inlets and every other row for exhaust. In this article, the double bed mode is proposed to be switched on during the batch drying process. By using the double bed mode, the air counter pressure increases by 69% and the travel distance of the air by 82%, based on computational fluid dynamics (CFD) simulations presented in this article. Hence, both the distance air travels in the grain bed is increased and due to the higher counter pressure the air flow rate decreases, allowing the better evaporation of water from the grain to the air transporting the vapor off.

1. Introduction

Moisture of grains of harvested cereal crops is often too high for long time storage. For instance, in Northern Europe the moisture (wet basis) of harvested wheat is 15–30% while the maximum permitted moisture level for one-year storage in the climate is 14.5% (Pabis et al., 1998). Therefore, the excessive water in the harvested grain must be removed as soon as possible, in order to prevent microbial activity.

Harvested grain is typically dried in convective grain dryers by forcing dry air flow through grain bed. While air flow passes through the grain bed, in narrow pores, water on the surface of the grains evaporates and the air flow transfers vapor off. The maximum possible amount of evaporated water in the air is limited by the dew point of the air: the relative humidity cannot exceed 100%.

Grain dryers can be divided into low temperature and high temperature dryers. In low temperature dryers, the ambient air is either used as is, or boosted by 5–15 °C. In high temperature dryers, the air temperature is remarkably higher than in ambient air, in range of 50–200 °C. The higher the temperature is, the higher the dew point is, hence the better the water transfers from the grain to the air. (Pabis et al., 1998).

In case heating energy is used to increase the air temperature before letting the air to flow through the grain bed, it is desired that the added energy is used efficiently to transfer moisture off the grain while passing through the grain bed. For instance, if the air flow is too high, relative humidity of outlet air is low and energy is wasted. Decreasing air flow speed, increasing grain bed depth or decreasing inlet air temperature are means to improve energy efficiency.

Energy required to dry the harvested grain is remarkable as is requires evaporation. In commercial high temperature grain dryers, the required amount of energy for drying equals to 6 kJ/water-kg, where water-kg is the amount of water to be removed from the grain (Suomi et al., 2003). This energy consists of heating the air, circulating the grain in the system and grain dust extraction systems. Alone in Finland, ca. 150 TJ energy is consumed for grain drying annually (Jokiniemi and Ahokas, 2014b). Various approaches to conserve energy in the grain dryers are proposed, like insulating the device including piping and using heat exchangers (Jokiniemi et al., 2016).

Convective grain dryer devices are classified based on the structure and the operating principle: a) batch grain dryers where grain batch stays in place all the time, b) continuous (grain) flow dryers where grain flow is dried in a single pass, and c) (grain) recirculating dryers where a grain batch is flowing through the convective elements multiple times.

Furthermore, the grain dryers can be classified based on how the air is tunneled through the grain. Cross-flow, concurrent-flow and mixed flow models are used. Cross-flow is typical in continuous flow dryers where air is pushed through the grain bed horizontally, while the grain flows downwards. Mixed flow can be used both in recirculating dryers and in continuous dryers. In these mixed flow dryers (MFD), the grain flows downwards and the air

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gets a way into the grain under roof-shaped (^) metal *inserts* installed in the box. As the grain does not fill the volume under roof-shaped inserts, the bypassing grain leaves *air ducts* in the grain that are used either for the *inlet air* or the *exhaust air*. The ends of the ducts are connected in air channel ends that connect air flow into a single pipe. (Pabis et al., 1998).

Computational fluid dynamics (CFD) based on numerical simulations and analysis is used to study many problems related to agricultural engineering. Bartzanas et al. (2013) list applications like soil & water, tillage, sprayers, harvesters and harvesting and greenhouses.

Mellmann et al. (2008) present principles of mathematical modeling for heat and mass transfer in mixed flow dryers and calibrate and validate that with the data collected in quasi-stationary experiments in their dryer test station. Later, Mellmann et al. (2011) studied distributions of moisture and residence time in mixed flow dryer by simulation, or by discrete element model. In that study, simulation was presented as a tool to improve the mechanical design of inlet ducts and it was also validated by pilot system. Weigler et al. (2012b) extended previous simulation results of mixed flow grain dryer by using CFD to simulate air flow through the grain bed. Scaar et al. (2016) presented more CFD simulation results of mixed flow dryers, extending the study from wheat to rapeseed, to cover different bed materials.

2. Motivation

In Northern Europe, the most common type of grain dryer is a high-temperature recirculating mixed flow dryer. The air is heated either by an oil burner or by a biofuel boiler. Recirculation of grain is considered necessary due to variation at moisture level of harvested grain and on the other hand the constant quality requirements in national grain trade.

In the conventional high-temperature recirculating mixed flow dryer, the air ducts are fixed, as well as the air flow and the air temperature. The volumetric recirculation rate of grain is also fixed by the metering device. The batch is dried and recirculated until the moisture is at the desired level. The characteristic curves of the batch process are presented in Fig. 1, presenting the relative humidity (RH) and the temperature of the exhaust air during the drying process. In the beginning, RH is high as the water evaporates easily from the surface of grains and the air flow limits the water transportation due to the dew point. Later on, the water diffusion in grain limits the water flux from the grain to the air, resulting in lowering RH in exhaust air. RH and the air temperature are linked: the lower the RH is, the less latent heat the air contains.

Jokiniemi et al. (2015) presented an air flow control system that reduces the air flow rate during the drying process. The underlying idea was to increase RH of the exhaust air, as the low RH is considered as the loss in the energy usage. With the reduced air flow, the water in the grain has more time to diffuse to the surface of individual grains and evaporate. Morey et al. (1976) and Jokiniemi and Ahokas (2014a) have proposed airflow rate control as a mean to reduce energy consumption in grain drying.

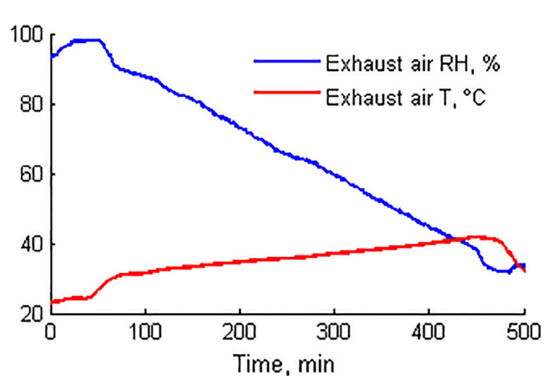

Fig. 1. Typical exhaust air properties in time function (). adapted from Jokiniemi et al., 2015

In this article, the proposed new method for air flow control is intended for *recirculating mixed flow dryer*. Normally, mixed flow dryers are operated in fixed mode air ducts where each duct is fixed either as the inlet, or the exhaust. In the normal mode, the rows of ducts are inlet or exhaust, alternately. In this article, the double bed mode is defined as an option for the normal operating mode that can be enabled on the fly. This requires that each duct may be selected either on inlet, exhaust or closed mode. In practice, at the end of each duct, a gate can be opened or closed as desired.

The double bed mode is realized by doubling the depth of the grain bed compared with the nominal, by closing every other duct and changing the location of inlet and exhaust ducts. The hypothesis is that (a) by increasing the depth of the grain bed creates a longer route for the air to gather vapor, (b) the increased grain bed depth increases air counter pressure, and (c) the increased counter pressure reduces air flow. Therefore, in the double bed mode, the air has more time to spend in the grain, thanks to increased distance and reduced velocity magnitude.

The research question is, how to the double bed mode affects to the air flow in the grain? How much longer the route of air flow would be and how much the counter pressure would increase? In this study, CFD is used as a tool to find answers to these questions.

Pipes and other air duct systems around the mixed flow dryer affect on the total counter pressure. Effect of piping should be considered separately when engineering the complete dryer system.

3. Dryer mechanics

3.1. Dimensions

The dryer studied in this article consists of identical metal inserts installed in an array. Every other row of inserts is offset by 50%. The dimensions of one insert are presented in Fig. 2, on the left. The grain flows under the insert in an angle. The center angle formed under the duct is defined as the bed angle and typical values of 115–125 degrees are reported by Weigler et al. (2012a). Thus, in this model the selected angle is 120 degrees. The spacing of the ducts is 320 mm in horizontal direction and 320 mm in the vertical direction, as presented in Fig. 2, on the right.

In commercial mixed flow dryers with size of 2×2 m, a typical recommended air flow rate is 500 m^3/h per duct. Scaling this to grain bed area under the duct of the dryer presented in Fig. 2, the typical average air velocity would be 0.35 m/s. This provides the magnitude of a typical air velocity used in commercial recirculating mixed flow dryers.

3.2. Grain parameters

In this study, wheat parameters are used in simulations. The approximate bulk density of wheat is 772 kg/m^3 and the air space/void/porosity in bulk is 40.1% ($\varepsilon = 0.401$), according to ASAE (2012). The resulting density of wheat (ρ) is 1290 kg/m^3.

3.3. Operating modes

Fig. 3 presents the simulated section of mixed flow dryer in 2D. For CFD purposes, the selected segment is a section that continues

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