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Energetic Analysis of Mixed-Flow Grain Dryers: a Case Study in Hungary

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Convective grain drying powered by natural gas is a highly energy-intensive process with a substantial impact on the secure storage of harvested grain. By improving energy efficiency and reducing natural gas consumption, it is possible to decrease the operation's ecological footprint by lowering CO_2 emissions. However, previous studies often analyse the drying process as a whole, giving less attention to individual processes. For instance, uneven drying can lead to issues during storage, such as microbial growth and dust accumulation. This paper presents an energetic analysis of mixed-flow grain dryers based on a case study in Hungary for the long term. It examines the fundamental physical characteristics of each dryer and identifies key modifications to ensure proper operation. The paper also introduces a precision drying method that allows fine-tuning of process parameters (e.g., airflow, grain flow) to optimise grain moisture content to the desired level based on large-scale continuous temperature measurements. These measurements can also validate previous modifications, enabling ongoing monitoring of optimal operating conditions via heatmaps.

1. Introduction

Grain drying is a widely used preservation process, with around 1,500 drying plants in Hungary. The annual gas consumption depends on the volume and moisture content of the crop produced, but on average, about 50,000 m^3 of natural gas per plant can be estimated in a season, which means an annual consumption of about 55 million m^3 of natural gas (i.e. about 593,000 MWh). For volume comparison, the monthly consumption figures in Hungary reported by the Hungarian Energy and Public Regulatory Utility Authority are shown in Figure 1. below from 2022. October report of Hungarian Energy and Public Utility Regulatory Authority. Most of the energy usage related to crop drying typically occurs in the September-December period. By reducing the amount of natural gas used, it is also possible to reduce the ecological footprint of the operation by reducing CO_2 emissions. If the efficiency of a grain dryer is increasing, it has to operate for a shorter period of time in the season, reducing the amount of electricity used too.

Energy consumption for moisture evaporation is a primary concern for grain dryers. Many scholars have analysed energy consumption, noting that it varies between dryer types and is influenced by the product type and desired quality (Mondal et al., 2021). Each dryer's design impacts energy use for efficient drying, as in the example of paddy drying in horizontal rotary dryers (Firouzi et al., 2017). Based on the method of energy transfer to the product, industrial dryers can be categorised into convective, contact, and emerging-field dryers. Specifically, mixed-flow dryers, a type of continuous dryer, are the most common in Hungary, making them ideal for analysing the energy performance of grain drying systems in this region.

To evaluate the energy performance of industrial drying, it is essential to consider energy loss, specific electrical and thermal energy consumption, energy utilisation ratio, energy efficiency, and thermal performance. Mondal and Sarker (2024) analysed energy use among various dryers and found the efficiency of mixed-flow dryers to be 80 %, noting a 12 % lower efficiency compared to other dryers. Mondal et al. (2021) further examined the drying characteristics and energy and exergy performance of mixed-flow dryers across a temperature range of 40-80 °C and air velocities of 3.0 and 6.0 m/s. They concluded that the energy utilisation ratio, exergy outflow, exergy loss, and exergy improvement potential all increased with higher drying temperatures.

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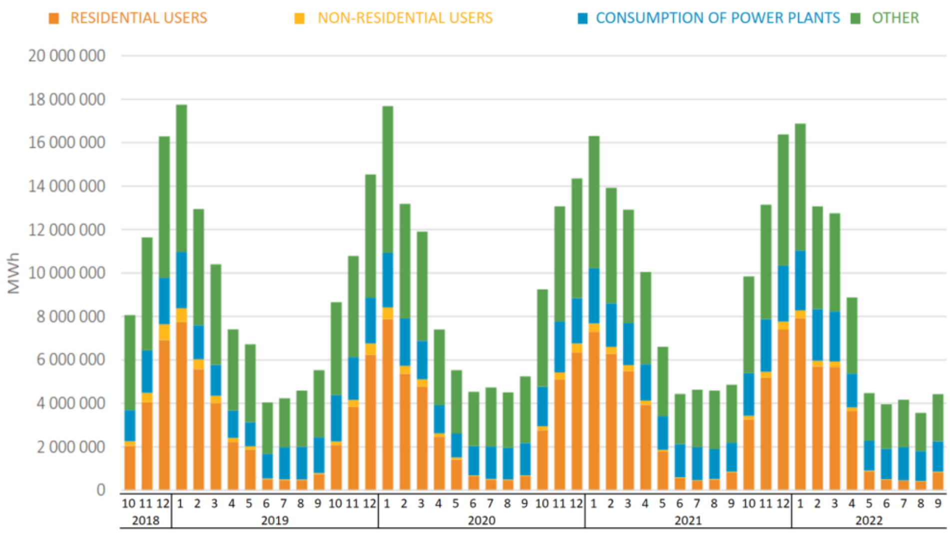

Figure 1: Structure and volume of natural gas consumption in Hungary in 2022

Previous studies on energetic analysis often consider the system as a whole, which can overlook specific energy losses and inefficiencies in individual processes in real-world applications. This study addresses this gap by providing a detailed energetic analysis of the drying process in a mixed-flow grain dryer over 6 y, based on a case study from real applications in Hungary. The contribution of the study is to propose a detailed assessment of a single drying process for mixed-flow grain dryers. A precision drying method is developed, allowing fine-tuning of process parameters (e.g., airflow, grain flow) to optimise grain moisture content to the desired level based on large-scale continuous temperature measurements. The aim of this study is to improve low energy efficiency, reduce energy consumption, and lower CO_2 emissions of the dryer application.

2. Methods and data

Mixed-flow grain dryers are the most widely used in Hungary due to the different power requirements associated with high crop averages and varying plant sizes. We can achieve the reduction of energy consumption at the crop dryer by gathering measurement data with the appropriate resolution required for the analysis of the water withdrawal process.

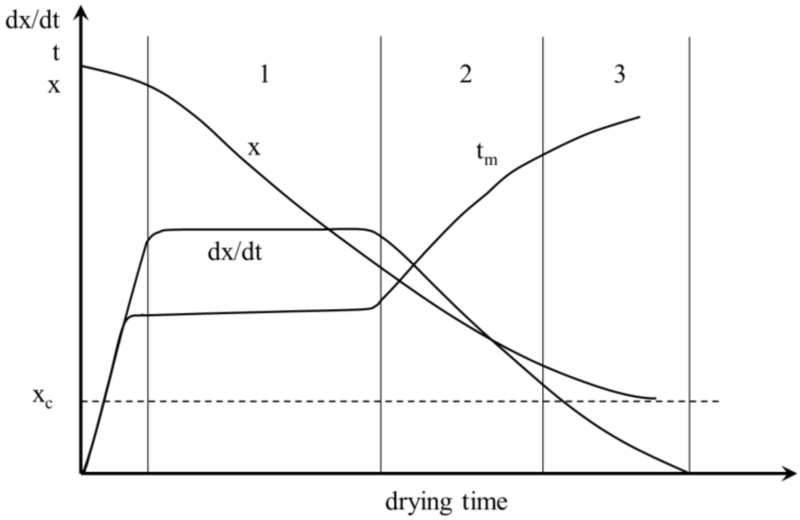

Figure 2: "tm" theoretical diagram, heat up of the crop-mass

It becomes possible to identify deviations in the characteristics of the water extraction process based on the measurement data. The theoretical drying process is shown in Figure 2:

1. The drying medium (homogenous temperature hot air) from the gas burner is evenly distributed through the product, which is slowly warming up each of the grain seeds from 8-10 °C to 48-55 °C during the water-distraction process.
2. All the heat given to the grain mass goes for the vaporisation of the moisture; the drying speed is constant. When the moisture decreases in the grain (x), the capillaries shrink, the evaporation zone contracts to the centre of the grain, and the mass temperature increases while the drying speed decreases.
3. The drying speed is still decreasing, the mass temperature is still increasing, and the average moisture content is under the "secure storage minimum".

The measurement method provides precise data from the outlet air ducts of the grain dryer, which can be used to identify the configuration of the dryer (temperature distribution, heat intensity, grain flow). An industrial temperature measurement system is used that is able to measure air temperature at more than 500 measurement points in parallel. However, the examples provided in the paper use fewer measurement points to illustrate the methodology more efficiently. It measures the temperature of hot air all over the surface passing through the mass of grain at the time of exit as shown in Figure 3. The gas burner is on the right side of the dryer shaft, and the drying air is going through the grain located in the shaft. The system measures the temperature of hot air passing through the mass of grain at the time of exit from the outlet air ducts; there is a strong correlation between the drying air temperature and the moisture content of the grain (the higher the temperature, the lower the moisture content of the grain).

The measurement data is able to point out the divergence of measurable parameters of grain driers from the optimal level. These parameters are homogenous temperature, airspeed and speed of the grain flow [2]. In case of divergence, the grain may get stuck, creating jams, get fire, be over-heated (in this case, the grain becomes fragmented and loses inner values) or under-heated (in this case, the grain does not lose enough moisture, causing mould in the warehouse). The sensors can identify grain jams and measure the intensity of heat inside the dryer shaft.

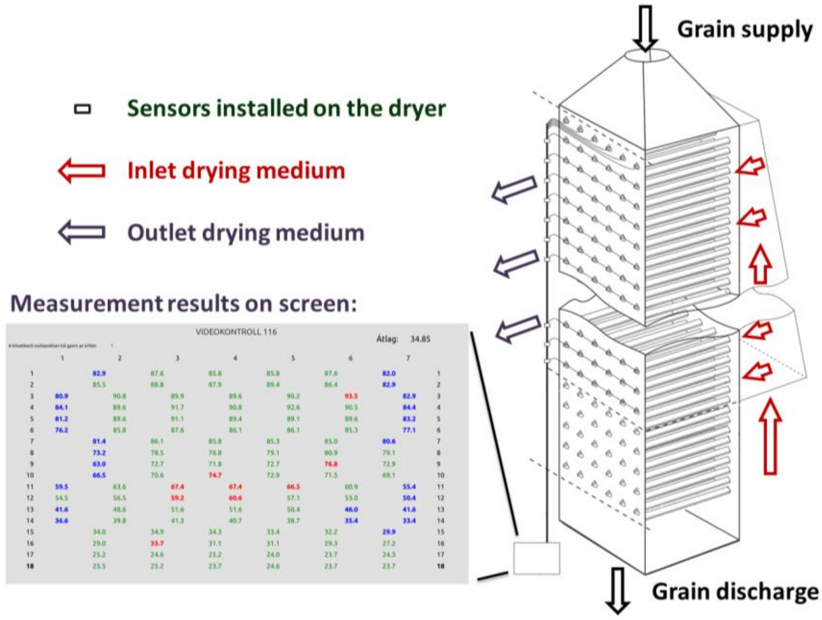

Figure 3: The measurement of temperature data

Precision drying is based on IT tools and data processing methods and provides much more information about the drying process than any other tool before. It provides strict control of the drying process to preserve grain quality, which is important for plant development, crop production and animal husbandry.

While preserving the quality of the grain, moisture removal must be gentle but with maximum efficiency. Experience shows that improvements based on the precision drying principle have, in most cases, increased performance and efficiency. To implement precision drying, more conditions should be kept near its optimum:

- Homogeneous heat load over the surface of the tower;
- Homogeneous grain-mass speed everywhere in the dryer shaft;
- Constant air pressure over the surface of the dryer.

3. Results and discussion

To show the physical causes, 3D modelling and computational fluid dynamics (CFD) are built, as shown in Figure 4. The applied simplification is that the grain loading and discharging part of the dryer is not included in the 3D model. The red part on the right is the warm side of the dryer; at the bottom, the gas is located to supply the heat for the drying medium. The blue part is the cold side of the dryer, where the drying medium saturated with moisture steps out from the grain. The condition of the homogenous pressure is the homogenous arrangement of air ducts on the surface. If the air ducts are not distributed uniformly on the surface of the drying shaft, that will cause a difference in air speeds and in drying efficiency. Simulations are performed to verify that there is a correlation between the distribution of air ducts, the higher temperatures and air velocity.

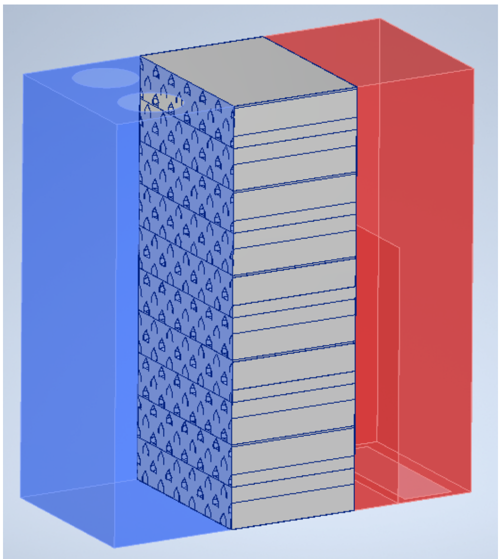

Figure 4: The simplified 3D model for the CFD simulation the cold-side (left) and warm-side (right)

The CFD simulation can be used to justify the effects that the so-called “thermal map” shows. The “thermal map” can be obtained about the vertical drying surface of the dryer shaft in front of the outlet air ducts (the “cold side” of the dryer), as shown in the left of Figure 5. A diagnosis can be set up based on the thermal map of the dryer. Conclusions can be drawn about the configuration of the hot side of the dryer (burner functionality, distribution of hot air in the air tunnel and on the surface, saturation of the air) and the dryer shaft (structural problems, airspeed). Pressure parameters are unbalanced on the drying surface (Figure 5. left), and further possible technical problems can be identified.

Figure 5: Thermal map of the same dryer before (left) and after optimisation (right)

The grain discharge speed and the drying air temperature are the parameters that can be set in most cases. This can be done by some control algorithms but also can be managed manually. The differences are always caused by some physical phenomenon. (Gottschalk, 2010). The left of Figure 6 shows an example where the asymmetry of the heat load is caused by the improper operation of the gas burner. Although the burner is not working properly, there is still quite a large space above the burner where the cold and hot air should mix, resulting in a homogenous temperature drying medium. The measurements clearly show that this expectation is not fulfilled; the drying medium is not mixing properly in this case, and there is a big temperature difference between the two sides. This temperature difference will cause an obvious difference in the moisture content of the grain coming from the two sides of the dryer, too. On the right side of the drying shaft, instead of 40 °C, 90 °C can be measured in whole seasons, which can cause enormous energy waste, over-drying and problems during warehousing (5-6 % difference of moisture content within one discharge cycle). This difference can be corrected by optimising the configuration of the warm side of the dryer, forcing the drying medium to mix properly.

Long-term measurements (more than ten drying seasons) are available for different types of grain dryers (20 different manufacturers). Some patterns can be identified in the thermal maps if the operation of the dryer differs from the optimal, as shown in the asymmetry of heat load in the dryer section (Figure 6 left) and the asymmetry of the discharge mechanism (Figure 6 right). The grain flowing into the centre of the dryer clearly flows faster than the layers at the side walls (Kocsis et al., 2011), where wall friction hinders the flow (Iroba, 2012). If this is possible in the grain dryer, the discharge mechanism should be adjusted to slow the grain flow in the middle.

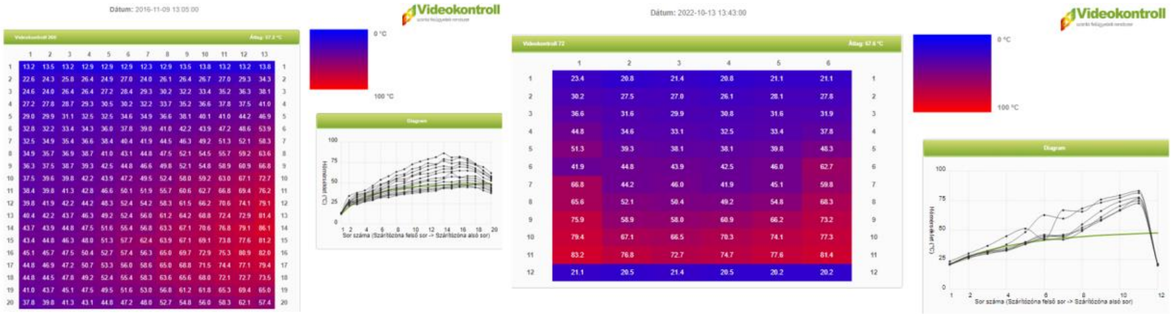

Figure 6: Asymmetry of heat load during maise drying (left), Asymmetry of the discharge mechanism (right)

The difference between the theoretical process (Figure 2) and the measurements is in the second step of the drying process. The drying speed is not constant in the second section but continuously increases with the decrease of the moisture content of the grain. The mixed-flow dryers are well established in the commercial market, so it is important to find out whether the drying process is optimal or, with further optimisation, if the energy efficiency and product quality can be improved. Unfavourable designs can cause uneven mass flow and air flow distributions, resulting in locally different drying conditions and, hence, uneven grain drying (Wiegler et al., 2011).

The issue of non-uniform distribution of air ducts is prevalent in many grain dryers in Hungary, as shown in Figure 7. If the air ducts are not distributed uniformly on the surface of the dryer, that will cause differences in air speeds and drying efficiency, too. It is necessary to find better solutions through development, but that is more important to increase the energy efficiency of the dryers established already in order to ensure sustainability. In this case, the over-heated horizontal sections occur because of the nonuniform distribution of air ducts; at irregular places, the air speed increases, and even the maise can be pulled out by the airflow from the dryer. The horizontal red bars mean energy loss. If the overheating can be stopped, then up to 30 % energy saving can be realised. According to Maier and Bakker-Arkema, there is still a need for research because the optimal shape, size, and location of air ducts in the drying bed of a mixed-flow dryer have not been established yet (Maier et al., 2002).

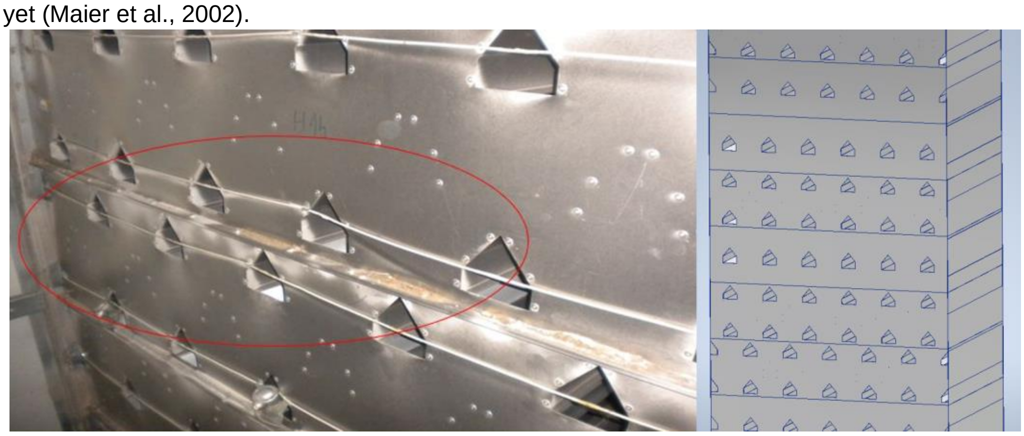

Figure 7: Uneven distribution of air ducts on the surface of the dryer (left) and the 3D model (right)

4. Conclusion

This paper analyses the energy efficiency of mixed-flow grain dryers through a long-term case study in Hungary. It focuses on identifying key modifications and precision drying methods to optimise grain moisture content, utilising large-scale temperature measurements to validate improvements and ensure optimal, eco-friendly dryer operation. The results of this study demonstrate that the non-uniform distribution of air ducts significantly impacts the drying efficiency and temperature uniformity in grain dryers. Through 3D modelling and CFD simulations, it was shown that uneven air duct distribution leads to differences in air speeds and drying performance. Thermal maps provided diagnostic insight, revealing issues such as asymmetry in heat load and discharge mechanisms. These disparities can result in uneven moisture content and significant energy losses, as highlighted by the 30 % potential energy savings if overheating is mitigated.
Precision drying makes the drying process transparent and more secure since it supplies information from all of the surfaces where the heated drying medium meets with the grain. This results in a transparent drying process, which ensures better quality of dried grain (proteins, vitamins not destructed), a more secure drying process (reduced fire hazard) and warehousing (no microbes, no dust) and less energy consumption and less CO_2 emission. Some examples were introduced that show the possible differences in the drying process. It's important to optimise the configuration of the warm side of the dryer and ensure proper mixing of the drying medium to achieve a homogeneous temperature profile. It's suggested that existing grain dryers be upgraded through improved air duct distribution, precision drying systems, enhanced mixing mechanisms, and advanced controls to boost energy efficiency, grain quality, and sustainability. The limitation of this work is that we have the observed data but do not yet have the simulation results. Future work will involve refining CFD models to simulate various dryer configurations and assessing the impact of air duct placement and airflow optimisation.

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