Efficiency analysis of the corn drying process in a periodic device

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Keywodrs: corn drying, experimental drying curve, thermal efficiency of installation, mobile dryer

ABSTRACT:
The paper presents a unique measuring analysis of corn grain drying in a small mobile device equipped with renewable fuel furnace. The theoretical and practical approach to grain drying were compared. It was shown that with the given device the grain moisture obtained was 12-14%. Such humidity is needed for permanent storage. On the basis of measurements and calculations it was proved that the thermal efficiency of the process is low and equals $\eta = 0.3$.
Experimental analysis will allow both validation of theoretical drying models for corn grain and determination of ways to improve the efficiency of the drying process. These will be presented in a separate paper.
1. INTRODUCTION

Drying process is widely used in many industries [1] for agricultural products, wood, fossil fuels (e.g. coal), fabrics, etc. [2]. In some industries, drying is the most power consuming process for a company [3]. That is why, similarly to other industries, effectiveness of the very process is a significant issue [4]. Drying may be done through the application of hot air, adsorption resources or cooling processes. The choice of solution depends on a kind of material to be dried or a temperature in which the material can be dried [5]. In this article the focus is on corn drying process. Corn grain is a biological material sensitive to temperature (shrinking, cracking, germination decrease, decline in nutritional value) and long storage in high humidity conditions (the loss of dry substance weight, growth of mould and microorganisms, germination decrease). Fungal spores have optimal growth conditions in grain contaminated with soil, dust and plant remains; therefore, cleaning grain is of great importance. The principal processes include grain breathing, which is connected to metabolic processes occurring in the grain. For example, the intensity of these processes is 35 times higher at 20% than 15% humidity. Breathing results in the losses of dry substance weight. With increasing temperature, microorganisms, bacteria and mould are growing, which leads to self-heating of the grain. Corn production in Poland is still on the increase. According to the UN Food and Agriculture Organisation (FAO), in 2010 corn cultivation area was 298 700 and in 2014 - 678 025 hectares, which gives over a double growth. The demand for grain drying equipment is also rising. A farmer can choose between selling wet grain at a lower price and drying on the farm to get a higher selling price. Besides moisture, the purchasing price is affected by the amount of contamination and the quantity of broken grains.

On the average, the price of corn of 14% moisture is 30% higher than the price of corn of 30% moisture. The cost of drying may constitute 40-60% of total corn production costs.

Corn drying specification:
- Corn is/may be considered mature if it has 35% moisture at most prior to being harvested.
- After harvest, the grain has 30%-40% moisture, which must be reduced to 14%. In comparison to other grains, three times more water must be drained.
- Due to the high initial moisture, thermal drying is exclusively recommended as only this kind allows reaching the required final humidity.
- The ratio of external heat and weight transfer surface to dried mass is low in comparison to other crops. The surface of 1 g of rye is 3200 mm², and of 1 g of corn – 960 mm².
- The values of harvested corn moisture can differ by even several percent in the substance harvested at the same period and from the same field.
- Corn displays a large variety of grain shapes and additionally, at machine harvesting, dry substance contains a large percentage of damaged grains and impurities.

2. MOBILE RE-CIRCULATING DRYERS

Mobile circulating dryers differ from non-circulating ones with the presence of a screw conveyor in the central part of the dryer. Its aim is to lift the grain weight from the lower part of the tank and transport it to the upper part. The circulation of the whole grain volume should take approximately 15 minutes. The most widely used dryers of this kind can dry from 10 to 20m³ of moist grain in one cycle. They are used on the farms which cannot afford more costly solutions (e.g. continuous dryers). Theoretically, such dryers may be used for any kind of grain, assuming that maximum drying temperature for the given kind is not exceeded. It should be noted that the screw conveyor may damage some grains, particularly when they are almost dry. During a single cycle, the dryer is able to dessicate 12 m³ of wet corn.
The dryer’s work cycle consists of several subsequent processes:
1. Loading the dryer
2. Drying process
3. Grain cooling
4. Unloading the dryer

To conduct a drying process it is necessary to provide hot air of approximately 100°C. Gas and oil burners or biomass boiler may be used for this task. The latter solution was used in the examined installation due to significantly lower operating costs. Figure 3 presents the dimensions of the dryer being analyzed whereas the installation diagram is shown in Fig. 4. The boiler is heated with a bale of straw of 1.2 m diameter and 1.2 m height, which is sufficient for approximately 1.5 hours of the dryer’s work depending on the moisture of the straw. Hot exhaust get to an exhaust – air exchanger and, after heating the air, it is vented to the flue. Drying air is fed to the boiler by the fan. Being heated in the boiler, it goes through an insulated channel of 600 mm diameter to an air chamber of 1680 mm height and 1520 mm diameter via an axial fan of 20 400 m³/h output and static pressure of 374 Pa. It goes further to a drying chamber through openings in perforated sheet placed on the vertical wall of the air chamber. The air flow is perpendicular to the direction of grain movement in the dryer. The grain outside the drying zone is mixed, which allows levelling out its moisture. Based on the dryer’s dimensions we can calculate the volume of grain being at the time in the drying zone.

Surrounded by hot air, a bed of corn gets warm and the desorption process starts. The air is cooled and moistened with the vapour from the grain surface. After passing through the corn bed and the outer casing of the dryer (made of perforated sheet as well), the air is not used further. The corn is in constant movement owing to a vertical screw jack of 300 mm diameter. The manufacturer says that the time for grain recirculation is approximately 10-12 minutes (depending on grain moisture). In the bottom part of the outer chamber there is a stirrer/mixing element whose aim is to prevent the flow to the screw jack being blocked.

When the grain reaches c. 16%-15% moisture, the cooling process starts. A throttle opens, which lets in the air of ambient temperature. It is mixed with warm air flowing from the cooled boiler. The grain must be cooled to prevent moisture condensation in the corn bed stored. The cooling process allows compensation of the batch humidity and its temperature. After the grain reaches temperature not exceeding the ambient temperature by 10K and the required 13-14% moisture, which allows safe storage, the process is complete.

### 3. MOISTURE MEASUREMENT

To perform the measurement of grain sample moisture, Dramiński moisture meter WD-12 was used. It applies the capacitive method of measuring humidity. Due to the fact that relative
permittivity for water is $\varepsilon = 81$ at the temperature of 20°C (at 100°C $\varepsilon = 55$), this parameter can be used as an indicator of the content of water in the tested sample.

4. MEASURING METHODS

The measurement was conducted for two drying cycles – Series 1 (the first day) and Series 2 (the second day). Moisture and temperature of the dried grains were taken every 30 minutes. The location of thermometers and of sample collection were show in Fig. 4. Temperature sensor in the air supply channel of the boiler is an element of thermostat whose task is to switch on an air blast if the temperature in the furnace drops. To measure air temperature in the air chamber and grain in the drying chamber there are two bimetallic thermometers of measurement ranges respectively: 0-200°C with graduations of 2°C and 0-120°C with graduations of 2°C. At Station 3, a sample of grain is collected to measure its temperature. The measurement of outdoor air temperature and humidity was conducted with PRO 3564 TERDENS hygrometer.

5. WYNIKI POMIARÓW

The amount of moisture in dried substance is usually expressed as the ratio of water weight to total product weight [9]:

$$X = \frac{m_w}{m_c} \, [kg / kg]$$  

(1)

where: $m_w$ – mass of water in the product, $m_c$ – total product weight.

The other/another method of establishing the moisture content is referencing water weight to dry weight in the product. This definition is more convenient in calculations [10]:

$$X' = \frac{m_w}{m_s}$$  

(2)

where:

The drying curve presented in diagram 5 illustrates the change in substance moisture content during the drying process. In determined conditions and convection drying it takes the following form/shape:

$$m_s = m_c - m_w$$  

(3)

In the drying process, moisture drops quickly in the initial stage and significantly more slowly at the end. The drying curve allows predicting the material drying time for larger batches provided the drying conditions remain unchanged. Drying curve graphs based on the measurement results including the cooling period when drying also occurs are shown in Figures 6 and 7.
Graph 7 exhibits a considerable decline in moisture content, 20% during the first 4-5 hours, and in the following 5 hours the drop is only about 6%. Initially, an increase in moisture is observed. The graph below shows sample changes in grain moisture for various values of „x” parameter indicating the thickness of the corn bed. Curve x = 0 illustrates the first layer which is supplied with air of the highest temperature and a very low amount of moisture. In such conditions, grain moisture plummets. Therefore, high temperatures are forbidden to use with motionless grains to prevent a drastic decrease in the grain quality.

Figure 8 shows a curve of drying rate. The curve resembles little the one presented in theoretical considerations, which is caused by the fact that the drying process in the installation tested is not conducted in optimal determined conditions. The temperature of the drying factor changes periodically due to the way the airflow is steered to the burning chamber as well as to the necessity of periodical loading the portion of fuel into the chamber.

From the graph we can estimate critical moisture, which in this case amounts to c.21%. Below that the drying rate decreases significantly. A line separating two drying periods is schematically marked in the graph below.

![Graph 7](image)

**Figure 8** Drying rate curve with the division into intervals – Series 2 [7]

### 5. BOILER THERMAL POWER

Biomass-powered boiler heats outer air to the temperature required in the drying process. Outside temperature, the air temperature in the air-discharge channel from the boiler and air humidity were measured to calculate the amount of heat transferred to the air. The data was used for calculating air enthalpy based on the relationship:

\[ h = c_{p,g} \cdot T + x(r + c_{p,w} \cdot T) \]  \hspace{1cm} (4)

Thermal output was calculated from:

\[ \dot{m}_g = \frac{V}{R_w \cdot \bar{p}(0,622 + x)} = 6,97 \left( \frac{kg}{s} \right) \]  \hspace{1cm} (5)

Heat output of heat source for two series (Series 1, Series 2) was respectively: 626.83 kW and 619.52 kW.

Total amount of heat delivered with the air to the dryer may be calculated by adding up the successive amounts of heat for each time interval:

\[ \dot{Q}_k = \dot{m}_g((h_{1+x})_2 - (h_{1+x})_1) \]  \hspace{1cm} (6)

The following figures were obtained:

\[ Q_c = \sum_{i=0}^{n} \dot{Q}_{k,i} \cdot t_i \]  \hspace{1cm} (7)

\[ Q_{c, Series 1} = 15686 \text{ MJ} \text{ and } Q_{c, Series 2} = 15612 \text{ MJ} \]

### 6. HEAT NECESSARY TO EVAPORATE MOISTURE

The data on moisture content of the grain may be used to assess the amount of power needed to evaporate it. The initial content was approximately 30.2% and 36.9% respectively for the first and second measurement series in relation to total weight. During drying the value of moisture dropped to 16.5% and 15.5%. The initial weight of dried grain was calculated based on the measured bulk density, which is \( \rho_z = 733 \text{ kg/m}^3 \) for both series. Therefore, the initial weight \( m_0 \) of the material to be dried is

\[ m_0 = \rho_z \cdot V_s = 8796 \text{ [kg]} \]  \hspace{1cm} (8)

The weight of evaporated moisture is expressed with a formula:

\[ m_w = m_0 \left(1 - \frac{1 - X_0}{1 - X_k}\right) \]  \hspace{1cm} (9)

where: \( X_0 \) – initial grain moisture [kg/kg], \( X_k \) – final grain moisture [kg/kg].

Obtained:

\[ m_{w, Series 1} = 1443 \text{ kg} \text{ and } m_{w, Series 2} = 2225 \text{ kg} \]

In the next stage, the amount of heat \( Q_w \) necessary to evaporate water, (assumed water vaporization heat \( r = 2500 \text{ kl/kg} \)):

\[ Q_w = m_w \cdot r \]  \hspace{1cm} (10)
Table 1: Values of enthalpy and thermal output of the boiler

<table>
<thead>
<tr>
<th>Series 1</th>
<th>Series 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>t [min]</td>
<td>h₁ [kJ/kg]</td>
</tr>
<tr>
<td>0</td>
<td>21.28</td>
</tr>
<tr>
<td>40</td>
<td>20.86</td>
</tr>
<tr>
<td>75</td>
<td>21.07</td>
</tr>
<tr>
<td>90</td>
<td>20.77</td>
</tr>
<tr>
<td>110</td>
<td>20.26</td>
</tr>
<tr>
<td>140</td>
<td>20.77</td>
</tr>
<tr>
<td>210</td>
<td>18.86</td>
</tr>
<tr>
<td>240</td>
<td>18.89</td>
</tr>
<tr>
<td>270</td>
<td>18.55</td>
</tr>
<tr>
<td>300</td>
<td>18.37</td>
</tr>
<tr>
<td>330</td>
<td>17.84</td>
</tr>
<tr>
<td>360</td>
<td>17.49</td>
</tr>
<tr>
<td>390</td>
<td>17.30</td>
</tr>
</tbody>
</table>

Obtained:

\[ Q_{w, Series\ 1} = 3608 \text{ MJ} \] and
\[ Q_{w, Series\ 2} = 5564 \text{ MJ} \]

7. INSTALLATION EFFICIENCY

The concept of power efficiency of the dryer is used to assess its work. It is defined as the ratio of useful energy to total amount of energy used in the drying process:

\[ \eta = \frac{Q_{useful}}{Q_{total}} \]  
\[ \eta = \frac{Q_w}{Q_c} \]  

(11)

(12)

In the case of the dryer under discussion, useful heat is \( Q_w \) heat used to evaporate moisture from the material, and total heat is the heat transferred by the boiler to the drying air. Equation 11 takes the form:

\[ \eta = \frac{Q_w}{Q_c} \]

(11)

The following values were obtained:

\[ \eta_{Series\ 1} = 0.23 \] and \[ \eta_{Series\ 2} = 0.35 \]

8. SPECIFIC HEAT CONSUMPTION

\( q \) indicates how much energy in the form of heat must be delivered to the drying process in order to evaporate 1 kg of water from the dried material. Specific heat consumption is often used to compare the drying efficiency of different models of dryers (12). The calculations results are presented in Table 2. For comparison, specific heat consumption for various types of corn drying are presented in Table 3 (13).

\[ q = \frac{Q_c}{m_w} \]  

(13)

Table 2: Unit heat consumption

<table>
<thead>
<tr>
<th>Measurements</th>
<th>Series 1</th>
<th>Series 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>q</td>
<td>10869 kJ/kg\text{water}</td>
<td>7014 kJ/kg\text{water}</td>
</tr>
</tbody>
</table>

Table 3: Unit heat consumption value for selected drying methods [1]

<table>
<thead>
<tr>
<th>Kind of drying</th>
<th>q [kJ/kg\text{water}]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dryer powered by unheated air</td>
<td>2300-2800</td>
</tr>
<tr>
<td>Low-temperature drying</td>
<td>2800-3500</td>
</tr>
<tr>
<td>Batch-in-bin, continuous flow-in-bin</td>
<td>3500-4700</td>
</tr>
<tr>
<td>High-temperature with air recirculation</td>
<td>4200-5100</td>
</tr>
<tr>
<td>High-temperature without air recirculation</td>
<td>4700-7000</td>
</tr>
<tr>
<td>Mixed drying, dryeration</td>
<td>3300-4200</td>
</tr>
</tbody>
</table>

Based on the conducted analysis, it can be stated that in comparison to other models, the tested mobile recirculating dryer has a relatively low efficiency and higher individual heat consumption for evaporating a kilogram of moisture from the grain. The efficiency in the first measurement series was 23%, and during the secondo one – 35%. Individual heat consumption for the first series is 10.87 MJ/kg of water, and for the second series 7.014 MJ/kg of water.
High-temperature dryers available on the market reach from 4 MJ/kg of water to 7 MJ/kg of water of individual heat consumption. The results obtained exceed this range, which indicates a necessity to introduce changes aimed at raising the dryer’s performance.

While analyzing the drying curve, it was noticed that grain moisture in the layer of the sample collected tends to grow in the initial stage of the dryer’s work, which can prove insufficient airflow through the batch and unwanted process of its humidification occurring.

**LITERATURE**


