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Analysis of Thermodynamic Events Taking Place during Vacuum Drying of Corn

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Abstract: Agricultural materials (LF products) can be considered biologically living organisms due to their structure and the composition of colloidal capillary-porous substances in them. They contain a large number of microscopic pores, microcapillaries and macrocapillaries, in which water is able to pass from the inner parts to the surface of the grain, and vice versa. Thus, it can be concluded that drying is an important and demanding aspect of agricultural production. To determine the optimal drying process for agricultural cereals from a nutritional, energy, economic and environmental point of view, it is necessary to address in detail the application of the technology of vacuum drying from a thermodynamic point of view. An analysis of the research results shows that drying temperature, harvest date and corn variety can significantly affect the properties of the main components of corn grain. This study investigates the individual technological parameters of the vacuum drying process for corn, such as the pressure used in the drying chamber, the grain drying temperature and the heating time, in order to achieve a maximum reduction in water content. The aim of the investigation is to determine the optimal parameters for the design of a functional prototype of a vacuum dryer. For this purpose, laboratory and semi-operational experiments using different types of organic materials are necessary. The structural design of the individual elements of the vacuum dryer is based on an analysis of laboratory and experimental tests, whose results are presented in this article.

Keywords: vacuum drying; high efficiency; agricultural crops; nutritional value; energy recovery

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1. Introduction

Agricultural crops can be considered biologically living organisms due to their structure and the composition of colloidal capillary-porous substances in them. They contain a large number of microscopic pores, microcapillaries and macrocapillaries, in which water can pass from the internal parts to the surface of the grain, and vice versa. After harvesting, agricultural crops go through a series of processes, such as receiving, cleaning, sorting and drying, in order to preserve the useful properties of their products during storage and processing. It can, therefore, be concluded that drying is an important and demanding aspect of agricultural production [1] for food producers and livestock breeders. The parameters of drying agricultural crops [2,3] have been investigated to increase the efficiency of the process or to ensure a minimum impact on the nutritional content. Among the wide spectrum of agricultural crops, attention is paid to the drying of cereals [4,5], lemons [6], olive pomaces [7], eggplants [8] and corn. Agricultural crops can also be used in ways other than those in the food industry, such as their use as biomass [9]. Maize is the most cultivated cereal in the world [10] according to the International Grains Council

(IGC). Its total global production reached almost 1200 million tons in 2020, covering a total area of 200 million ha. Maize is considered an important crop [11] and is used in several fields, including the food industry, animal production and agricultural production. New procedures and technological solutions for corn drying have been compared with the classical approach, for example, in [12]. The advantage of low-temperature vacuum drying has been demonstrated, mainly due to the small influence of this process on the nutritional value of corn [13]. The key principle is to understand the composition of corn grains and their behavior during the drying process [14], with a focus on the moisture transfer process throughout the grain. In major agricultural countries, maize drying entails a reduction in moisture from values of about 17–30% to values between 8 and 14%, depending on the type of grain [15]. The authors of [9] reported that a moisture content below 14% and a storage temperature below 25 °C preserved the physico-chemical quality of corn grains and achieved better processing results for corn products.

Corn grain [16] contains dry matter [17,18] (carbohydrates, proteins, fats, minerals, vitamins and enzymes) and water. Temperature is an important parameter that affects the dynamics of the drying process and its energy consumption. It also has an impact on the final nutritional value of dried corn. Proteins, sugars, vitamins and enzymes are very sensitive to elevated temperatures.

For the evaporation of water, it is necessary to spend a certain amount of energy. This amount of energy is largely dependent on the temperature of the dried grains [19]. Depending on the requirements of the nutritional value of corn after drying, it is necessary to prevent overheating of the grain core and damage to its surface layer. Several studies have discussed this issue in the drying process [20–23].

In a conventional dryer, the material to be dried is heated by an air stream until moisture reaches the surface of the material [24–26]. The quality criterion for the drying process depends on the psychometric properties of the drying air. This is an energy-intensive process. In vacuum drying, "sensitive" agricultural crops are dried under reduced pressure in a vacuum.

In a vacuum dryer, water evaporates at a lower temperature due to reduced pressure. For example, at an atmospheric air pressure of 100 kPa, the boiling point of water is 99.6 °C, and, at a reduced pressure, e.g., 10 kPa, the boiling point is 45.8 °C. This reduces the energy required to reach the drying temperature.

Vacuum drying [27,28] has a number of advantages over air drying. It is mainly used for drying products with large surface areas, such as hygroscopic materials in the production of plastics [29,30], chemicals, food [28,31] and pharmaceutical products [32–34]. During the production of fruit concentrates or lyophilization of coffee or fruit, the consistency, the content of vitamins and the taste of the product are preserved. In [10], it is assumed that the use of a vacuum in a drying chamber reduces the risk of thermal stress on the corn grain itself. Vacuum drying has additional advantages, including a significant reduction in the drying time, a reduction in energy consumption, an avoidance of material degradation due to long-term heat load in the air stream, lower operation and maintenance requirements and smaller built-in dimensions of the dryer [12,35].

The efficiency of vacuum drying depends on the input moisture content of the crop being dried [36]. To optimally set the drying process from the nutritional, energy, economic and environmental points of view, it is necessary to address in detail the application of the vacuum drying technology in a thermodynamic context. A previous study [37] shows that drying temperature, harvest date and corn variety can significantly affect the properties of the main components of corn grain, with a possible impact on its further usefulness.

It is analytically difficult to optimize the process of vacuum drying corn and other agricultural cereals. In this process, it is necessary to determine the pressure of the drying medium, the temperature and the drying time of the grain to achieve maximum moisture reduction. Laboratory experiments using various types of organic materials are essential. The aim of this study is to experimentally investigate the drying process of maize under reduced pressure and temperature in a vacuum. The appropriate conditions for the implementation of the heating and drying phases are determined separately. The parameters being manipulated are the pressure in the vacuum chamber, the drying time interval and the number of drying cycles. The research results of this study are used as input data for the design of a prototype dryer working under the principle of vacuum drying.

One of the results of this study is the increased drying efficiency obtained by using repeated cycles, and the prototype dryer is being developed to reflect this fact. Its main benefit is the heat recovery between cycles. The components of the dryer under development are designed based on the results of this study.

2. Material and Methods

A simplified physical model of a vacuum dryer was installed in the laboratory of the Institute of Production Systems, Environmental Technology and Quality Management of the Faculty of Engineering of the Slovak University of Technology (STU) in Bratislava, Slovakia (Figure 1). The model was used to analyze the thermodynamic events taking place during the vacuum drying of corn.

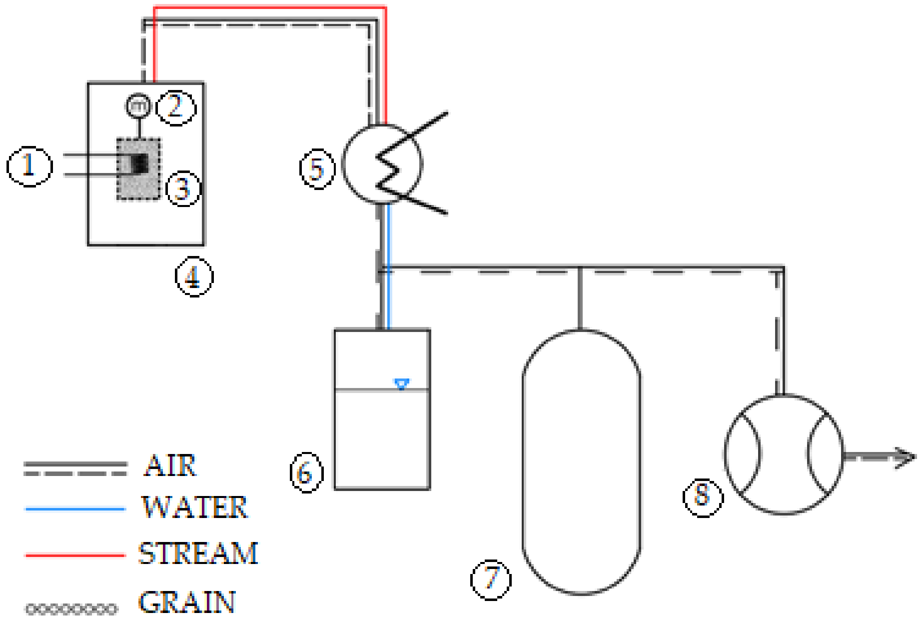

Figure 1. Diagram of the simplified physical model of a vacuum dryer [38], where 1—electric heating, 2—tensometric balance, 3—perforated basket for the grain, 4—vacuum chamber, 5—condenser, 6—condensate tank, 7—vacuum air reservoir and 8—vacuum pump.

A perforated grain basket is suspended in the vacuum chamber on a tensometric scale. A specially shaped heating coil is installed in the basket for even heating of the measured sample. The desired heating coil power is regulated by a rheostat. During the preparation of a corn sample, the temperature sensors and the selected corn grain are inserted into the basket. Heating of the corn grain in the basket by the heating coil provides informative data regarding the vacuum drying process.

The required pressure in the vacuum system is provided by a water circulation pump and a vacuum air reservoir. In the vacuum system, air with humidity, which is increased by steam evaporated from corn kernels, flows through the primary side of the condenser. Condensed water then flows into the condensate collection tank.

After the end of the vacuum drying process, the corn sample is removed from the vacuum chamber and dried on a sieve under atmospheric conditions.

Vacuum Drying of Corn under Laboratory Conditions

The thermodynamic events occurring during vacuum drying were analyzed using corn samples. The corn samples were harvested in September 2021 and had a moisture content of 14.46% [38]. Kernels were naturally dried on corn cobs before measurements were taken.

Vacuum drying of corn in an experimental facility consists of the following stages:

- Preparation of a corn sample;
- Heating of the corn sample in a vacuum chamber;
- Evaporation of water from corn kernels in the vacuum chamber;
- Drying of the corn sample on a sieve.

During the individual measurements of the corn samples under vacuum drying, the values of the following parameters were measured:

t_c—temperature of the corn sample;
t_g—temperature of the selected corn grain;
t_h—temperature of the electrically heated coils;
t—temperature of moist air in the vacuum chamber;
p—pressure of moist air in the vacuum chamber.

The weight of each corn sample was measured using a laboratory scale at different time points:

m_{c1}—at the beginning of the measurement;
m_{c2}—after removing the sample from the vacuum chamber;
m_{c3}—after drying the sample on the sieve.

Considering the goal of the research task—to structurally design, manufacture and operate a prototype of a mobile vacuum dryer intended for drying corn—the methodology of the experiment was aimed at optimizing the vacuum drying process.

Using a simplified physical model of the vacuum dryer, individual measurements of the corn samples under vacuum drying were performed so that the influence of the following variables could be analyzed:

- Pressure p_1 in the vacuum chamber during the heating of a corn sample;
- Pressure p_2 in the vacuum chamber during the evaporation of water from the corn sample;
- Changes in the temperature t_{c2} of the corn sample due to the regulation of the power input by the coils during the evaporation of water from the corn sample;
- Time τ_2 of heating during the evaporation of water from the corn sample;
- Number of cycles of evaporation of water from the corn sample to reduce moisture.

A total of 14 measurements of the corn samples were carried out using the experimental equipment of the vacuum dryer. In February 2022, measurements no. 1 to no. 9 were performed, and then measurements no. 10 to no. 14 were carried out in April 2022. The values of the measured variables obtained from the individual measurements of the corn samples under vacuum drying are listed in Table 1.

During measurements no. 1 to no. 14, the moisture content of the samples was measured before drying (w_{c1}), after removal from the vacuum chamber (w_{c2}) and after the additional evaporation of water from the surface of the grains that were placed loosely on a sieve (w_{c3}). The accuracy of the class I hygrometer used in this study, as a typical instrument used in commercial transactions, was subjected to verification. Uncertainties of the hygrometer measurements affected the corn moisture values w_{c1}, w_{c2} and w_{c3}. For example, measurements no. 9 to no. 14 were carried out over a period of 7 days in April 2022, while the detected moisture values w_{c1} of the corn samples at the beginning of the measurement differed by 6.7%.

During the verification of the metrological accuracy of the hygrometer, the testing methods were defined. Determination of the moisture content of five samples with the same measured corn moisture content was carried out using the reference gravimetric method under the conditions listed in Table 2.

Table 1. Values of selected measured variables during vacuum drying of corn. p_1 is the pressure in the vacuum chamber during the heating of a corn sample; t_{c1max} is the temperature of the corn sample; t_{c2max} is the change in the temperature t_{c2} of the corn sample due to the regulation of the power input by the coils during the evaporation of water from corn grains; t_{cavg} is the average temperature of the corn sample; p_{avg} is the average pressure of moist air in the vacuum chamber; τ_2 is the drying period; m_{c1} is the weight of the corn sample at the beginning of the measurement; m_{c2} is the weight of the corn sample after being removed from the vacuum chamber; and m_{c3} is the weight of the corn sample after drying the sample on a sieve.

Measurement No.	p_1	t_{c1max} t_{c2max}	p_{avg}	$t_{c\ avg}$	t_{c2min}	$(t_{c2}–t_s)_{min}$	τ_2	m_{c1}	m_{c2}	m_{c3}
	(kPa)	**(°C)**	**(kPa)**	**(°C)**	**(°C)**	**(°C)**	**(h:min)**	**(g)**	**(g)**	**(g)**
1	100.76	55.2	5.82	45.6	38.8	1.9	1:06	1300.00	1293.78	1292.70
2	102.77	50.9	5.91	43.9	38.9	2.1	0:45	1300.00	1295.00	1293.93
3	102.45	52.7	6.62	44.9	39.1	2.3	0:54	1300.00	1294.80	1293.65
4	101.95	60.3	9.19	52.4	46.9	1.7	0:37	1300.00	1292.82	1291.60
5	101.66	60.6	9.81	53.8	48.4	0.6	0:34	1300.00	1292.00	1290.45
6	101.28	59.8	9.51	53.8	48.8	3.0	0:33	1300.00	1291.49	1290.20
7	102.06	61.6	9.35	61.6	62.7	17.6	0:57	1300.00	1294.20	1293.00
8	101.95	62.6	9.26	61.5	60.2	15.6	0:56	1300.00	1290.36	1289.29
9 over 2 cycles	101.93	60.5	8.66	54.1	48.6	4.6	1:26	1300.00	1282.93	1281.80
9 in 1st cycle	101.93	60.5	9.02	54.0	48.7	3.6	0:40	1300.00	1289.80	1289.80
9 in 2nd cycle	101.69	60.4	8.31	54.1	48.6	5.5	0:46	1289.80	1282.86	1281.80
10	100.74	60.0	9.74	54.2	48.7	2.6	0:48	1300.00	1295.00	1294.10
11	9.90	44.7/61.4	9.70	55.2	48.5	2.2	1:29	1300.00	1297.11	1295.90
12	102.08	60.0	8.41	59.5	59.5	16.9	0:28	1300.00	1296.86	1295.80
13	101.95	60.5	9.42	60.7	59.6	14.2	0:42	1300.00	1295.80	1294.80
14	100.00	60.1	8.73	61.0	62.8	18.2	0:58	1300.00	1295.90	1294.70

Table 2. Conditions for determining the metrological accuracy of the class I hygrometer used for measuring the water content of the corn samples.

Conditions for Determining the Metrological Accuracy of the Hygrometer	
Pre-drying temperature (°C)	60 ± 1
Pre-drying time (min)	360
Sample weight (g)	10
Kernel	whole
Drying temperature (°C)	130 ± 1
Drying time (min)	240
Sample weight (g)	5
Kernel	ground

The corn samples were prepared just before the measurements by separating the kernels from the husks. The initial moisture w_{c1} of the reference corn samples during the two periods of the experiment was as follows (Table 3):

- w_{c1} = 10.487% for measurements no. 1 to no. 9 carried out in February 2022;
- w_{c1} = 8.858% for measurements no. 10 to no. 14 carried out in April 2022.

The corn sample (Figure 2) was placed in the perforated basket at an m_{c1} of 1300 g, the temperature t_{c1min} was in the range of 16 °C to 21 °C and the moisture content w_{c1} was determined. In the basket, a temperature sensor was placed at the middle height of the sample to continuously detect the temperature of the corn sample.

From the experimentally determined weights m_{c1}, m_{c2} and m_{c3} of a corn sample during its drying, it is possible to use the corresponding moisture value w_{c1} to calculate the dry weight m_d and the moisture content values w_{c2} and w_{c3} of the corn sample.

Table 3. Results of the weight of dry matter and the water content w_c in a representative sample of corn determined using the reference gravimetric method.

Corn Water Content Measurement Period	February 2022	April 2022
Weight of corn sample, m_c (g)	10,000	9996
Sample weight after pre-drying (g)	9800	9866
Sample weight before drying (g)	5000	5002
Sample weight after drying (g)	4567	4619
Weight of dry matter in the sample, m_d (g)	8951	9111
Water content of the corn sample, w_c (%)	10,487	8858

(**a**) (**b**)

Figure 2. Perforated grain basket and electric heating coils for grain heating [38]: (**a**) detail and (**b**) scale for determining the weight of the grain sample, along with the basket and the heating coils.

The mass of dry matter m_d is determined using the following equation:

$$m_d = m_{c1} \cdot \left(1 - \frac{w_{c1}}{100}\right) \text{ (g)} \quad (1)$$

The relative humidity w_{ci} of the corn sample (relative water content) is defined as the ratio of the weights of m_{wi} of water and m_{c1} of the corn sample:

$$w_{ci} = 100 \cdot \left(\frac{m_{wi}}{m_{ci}}\right) = 100 \cdot \left(\frac{m_{ci} - m_d}{m_{ci}}\right) = 100 \cdot \left(1 - \frac{m_d}{m_{ci}}\right) \text{ (\%)} \quad (2)$$

The moisture content w_{c2} of the corn sample after removing the sample from the vacuum chamber and the moisture content w_{c3} after drying the sample on the sieve are calculated using the gravimetric method based on the dry weight $\mathrm{m_d}$ and the measured weights m_{c2} and m_{c3}, respectively (Table 1).

The individual measurements of the corn samples during vacuum drying, which took place with the selected modes of heating and evaporation of water from the corn grains, can be compared with each other based on the following values:

- The difference Δw_c in the corn moisture content w_{c1} at the beginning of the measurement and w_{c3} after drying the sample on the sieve:

$$\Delta w_c = w_{c1} - w_{c3} \ (\%) \tag{3}$$

- The relative moisture difference Δw_{crel} of the corn sample as defined by the proportion of the difference Δw_c and the moisture content of the corn sample w_{c1} at the beginning of the measurement:

$$\Delta w_{crel} = 100 \cdot \frac{w_{c1} - w_{c3}}{w_{c1}} \ (\%) \tag{4}$$

Leakages in the vacuum system caused an increase in pressure p_i during corn heating (i = 1) and vacuum drying (i = 2). The pressure in the system dropped after the pump was restarted. The pressure p_i during the phases of heating and vacuum drying was characterized based on its mean value p_{iavg}.

The temperature t_{c1max} (60 + 3) °C was determined for all phases of vacuum drying. The corn samples were heated at atmospheric pressure. The exception was during measurement no. 11, wherein the mean pressure in the vacuum chamber was p_{1avg} = 9.90 kPa during the heating of the sample. The temperature t_{c1max} was the same as the temperature t_{c2max} at the beginning of the vacuum drying of the corn samples.

Water from the corn kernels during measurements no. 1 to no. 3 was evaporated at a pressure p_{2avg} (5.82 ÷ 6.62) kPa. During these measurements, the corn samples were heated to a temperature t_{c1max} of (50.9 ÷ 55.2) °C. Measurements no. 4 to no. 14 took place at pressures p_{2avg} ranging from 8.31 kPa to 9.81 kPa, while the temperature t_{c1max} of the corn samples at the end of the heating ranged from 59.8 to 62.6 °C.

Heat was removed from the dry matter of the grain, and the temperature t_{c2} of the corn samples gradually decreased to the value of t_{c2min}. The drop in temperature t_{c2} was dependent on the power input of the coils. The temperature t_{c1max} during heating was set so that, even at the end of the evaporation of water from the corn kernels, the temperature t_{c2} min was higher than the temperature $t_{s(p2)}$ of water saturation at pressure p_2.

During the vacuum drying of the corn samples for measurements no. 1 to no. 6 and measurements no. 9 to no. 11, the coil power was reduced. Vacuum drying was terminated when the difference $(t_{c2}–t_s)_{min}$ between the corn temperature and water saturation temperature was in the range of 0.6–5.5 °C.

During measurements no. 7, no. 8 and no. 12 to no. 14, the spiral input power compensated for the heat of evaporation of water from the corn grains via vacuum drying. The temperature difference t_{c1max} at the beginning and t_{c2min} at the end of vacuum drying was in the range of −2.7–2.4 °C. At the end of vacuum drying, the difference $(t_{c2}–t_s)_{min}$ was in the range of 14.2 °C to 18.2 °C.

Vacuum drying of each corn sample was completed by increasing the pressure p_3 in the vacuum chamber to the value of atmospheric pressure. Subsequently, after 5 min, the corn sample was taken out of the vacuum chamber and weighed. The loss of water from the grains reduced the weight of the corn sample to the value of m_{c2}.

In the last stage of drying, each corn sample was placed loosely on a sieve. Water from the surface of the corn kernels was allowed to evaporate into the air for 60 min. After finishing all stages of the vacuum drying of the corn sample, its final weight m_{c3} was determined.

For measurements no. 1 to no. 14, Table 1 lists the values of the weight m_{c1} of the corn samples at the beginning of the measurement, m_{c2} after removing the samples from the vacuum chamber and m_{c3} after drying the samples on the sieve. These weights of the corn samples formed the basis for calculating the weight of dry matter m_d of the corn samples and the corresponding moisture contents w_{c2} and w_{c3} during their drying.

3. Results

The reference gravimetric method was used to determine the initial moisture w_{c1} of representative samples of corn that were dried in two periods: February and April 2022 (Table 3). According to the experimentally determined weights m_{c1}, m_{c2} and m_{c3} of the corn samples (Table 1) and Equations (1)–(4), the weight of dry matter m_d was calculated based on the weight w_{c2} of the corn samples after removal from the vacuum chamber, w_{c3} after drying the samples on the sieve, the moisture difference Δw_c and the relative moisture difference Δw_{crel} of the corn samples.

The calculated moisture values w_{c1}, w_{c2} and w_{c3} of the corn samples during vacuum drying for measurements no. 1 to no. 14 are summarized in Table 4. The moisture values w_{c1} at the beginning and w_{c3} after the completion of vacuum drying for the individual measurements are shown in Figure 3. The difference in humidity w_{c1}–w_{c2} was determined from the moisture content during the heating of the corn sample and the moisture content during the evaporation of water from the grains in the vacuum chamber, and w_{c2}–w_{c3} was determined from the moisture content when the sample was removed from the vacuum chamber and the moisture content at the end of drying the sample on the sieve. In Table 4 and Figure 4, the difference in humidity w_{c1}–w_{c3} as Δw_c and the relative difference $\Delta w_{c\ rel}$ are given for the reference corn samples.

Table 4. Calculated water content w_c of corn during vacuum drying. m_d is the weight of dry matter of the sample; w_{c1} is the initial moisture content of the sample; w_{c2} is the moisture content after removal from the vacuum chamber; w_{c3} is the moisture content after drying the sample on the sieve; Δw_c is the moisture difference; and Δw_{crel} is the relative moisture difference of the corn sample.

Measurement No.	m_d	w_{c1}	w_{c2}	w_{c3}	Δw_c	$\Delta w_{c\ rel}$
	(g)	**(%)**	**(%)**	**(%)**	**(%)**	**(%)**
1	1163.67	10.49	10.06	9.98	0.51	4.82
2	1163.67	10.49	10.14	10.07	0.42	4.00
3	1163.67	10.49	10.13	10.05	0.44	4.19
4	1163.67	10.49	9.99	9.90	0.58	5.55
5	1163.67	10.49	9.93	9.82	0.66	6.32
6	1163.67	10.49	9.90	9.81	0.68	6.48
7	1163.67	10.49	10.09	10.00	0.48	4.62
8	1163.67	10.49	9.82	9.74	0.74	7.09
9 over 2 cycles	1163.67	10.49	9.30	9.22	1.27	12.12
9 in 1st cycle	1163.67	10.49	9.78	9.78	0.71	6.75
9 in 2nd cycle	1163.67	9.78	9.29	9.22	0.56	5.76
10	1184.85	8.86	8.51	8.44	0.42	4.69
11	1184.85	8.86	8.65	8.57	0.29	3.26
12	1184.85	8.86	8.64	8.56	0.295	3.335
13	1184.85	8.86	8.56	8.49	0.366	4.132
14	1184.85	8.86	8.57	8.48	0.373	4.212

The efficiency of vacuum drying depends on the input moisture of agricultural grains [39]. It should be noted that the moisture measurements of the corn samples using a simplified laboratory model of a vacuum dryer were carried out in the spring months. During the natural drying of corn kernels on cobs, the values of moisture difference Δw_c and relative moisture difference Δw_{crel} were affected by the low initial moisture w_{c1} of the corn samples, which was 10.49% in February 2022 and 8.86% in April 2022.

3.1. *Effect of Vacuum Chamber Pressure on Reduction in Moisture during Heating of Corn Sample*

The influence of pressure p_1 in the vacuum chamber on the reduction in moisture during the heating of the corn samples was experimentally determined based on measurements no. 10 and no. 11.

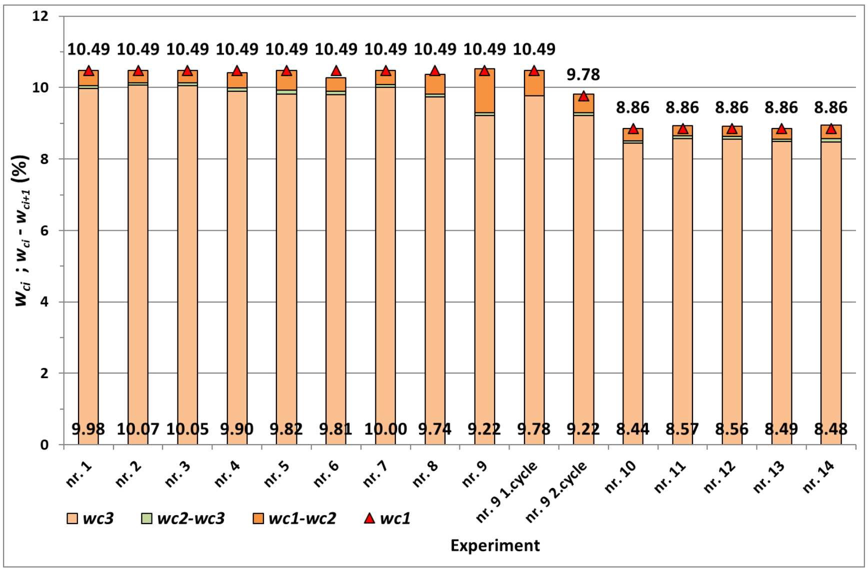

Figure 3. Corn sample water content w_{c1} at the beginning of the measurement, w_{c3} after drying the sample on the sieve and differences in water content w_{c1}–w_{c2} and w_{c2}–w_{c3} for measurements no. 1 to no. 14.

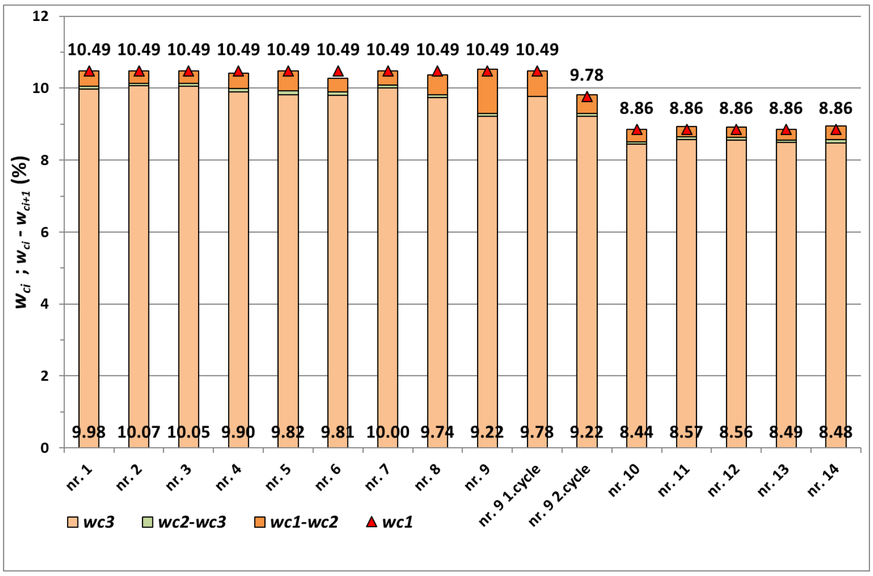

Figure 4. Difference in water content Δw_c and relative difference in water content Δw_{crel} of the corn samples during measurements no. 1 to no. 14.

During measurement no. 10 (Figure 5), the corn sample was heated from a temperature t_{c1min} of 17.8 °C to t_{c1max} of 60.0 °C under an atmospheric pressure p_1 of 100.74 kPa in the vacuum chamber. Depending on the power input of the coils, heating took 1:24 h. Vacuum drying of the corn sample took place under a pressure $p_{2\ and\ vg}$ of 9.74 kPa. Evaporation of water from the corn kernels at a reduced spiral power took 0:48 h, while the temperature t_{c2min} of the corn sample dropped to 48.7 °C, and the difference $(t_{c2}–t_s)_{min}$ between the corn temperature and the water saturation temperature at pressure p_2 was 2.6 °C. By vacuum drying the corn sample, the difference Δw_c between the corn moisture content w_{c1} at the beginning of the measurement and w_{c3} after drying the sample on the sieve was 0.42%, which corresponded to a relative moisture difference $\Delta w_{c\ rel}$ of 4.69%.

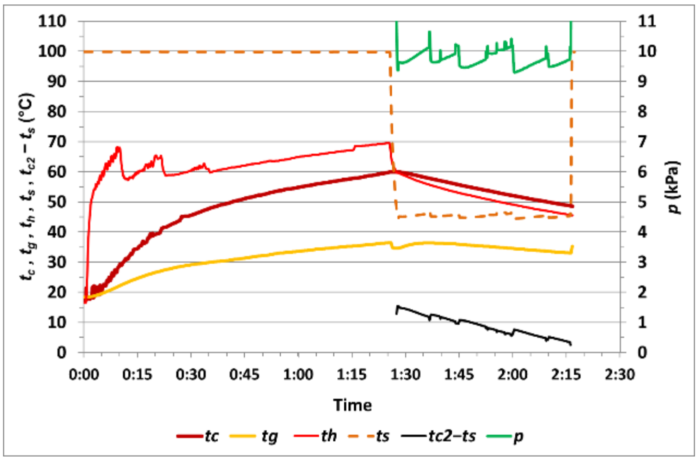

Figure 5. Measurement no. 6: Δw_c = 0.68% and $\Delta w_{c\ rel}$ = 6.48%.

Measurement no. 11 (Figure 6) of the corn sample took place under a medium pressure p_{1avg} of 9.90 kPa during heating and under a pressure p_{2avg} of 9.70 kPa during vacuum drying. The temperature t_{c1min} was 20.2 °C after 0:23 h of heating and rose to the value t_{c1max} of 44.7 °C. Vacuum drying lasted 1:29 h, while t_{c2max} was 61.4 °C, t_{c2min} was 48.5 °C and the temperature difference $(t_{c2}–t_s)_{min}$ was 2.2 °C. During the corn drying process, the moisture difference Δw_c of the corn sample was 0.29%, and the relative difference $\Delta w_{c\ rel}$ was 3.26%.

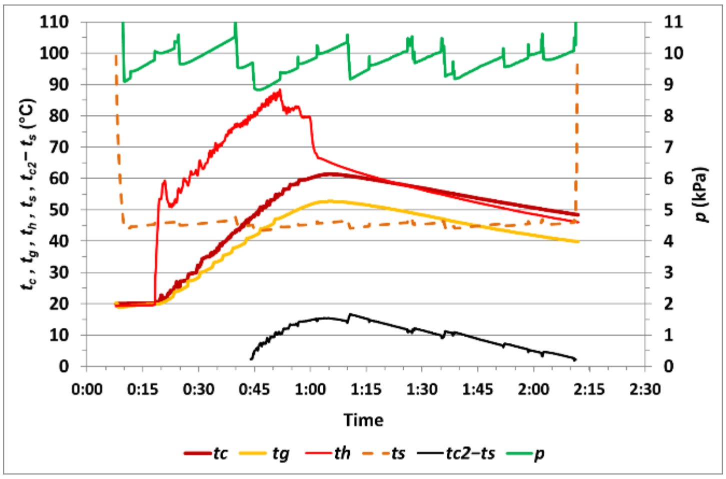

Figure 6. Measurement no. 11: Δw_c = 0.29% and $\Delta w_{c\ rel}$ = 3.26%.

3.2. Effect of Vacuum Chamber Pressure on Reduction in Moisture during Evaporation of Water from Corn Sample

From the point of view of the heating of the corn samples under atmospheric pressure and the phase of evaporation of water from corn kernels at a reduced spiral power, the values of measurements no. 1 to no. 6 were similar. The effect of pressure p_2 in the vacuum chamber on the reduction in moisture during the evaporation of water from the corn samples was experimentally determined based on measurements no. 1 to no. 3, when the mean pressure p_{2avg} was in the range of 5.82–6.62 kPa, while measurements no. 4 to no. 6 took place under pressure p_{2avg} in the range of 9.19–9.81 kPa. Figure 7 shows the course of the values detected during measurement no. 2, and Figure 8 shows the values of measurement no. 4.

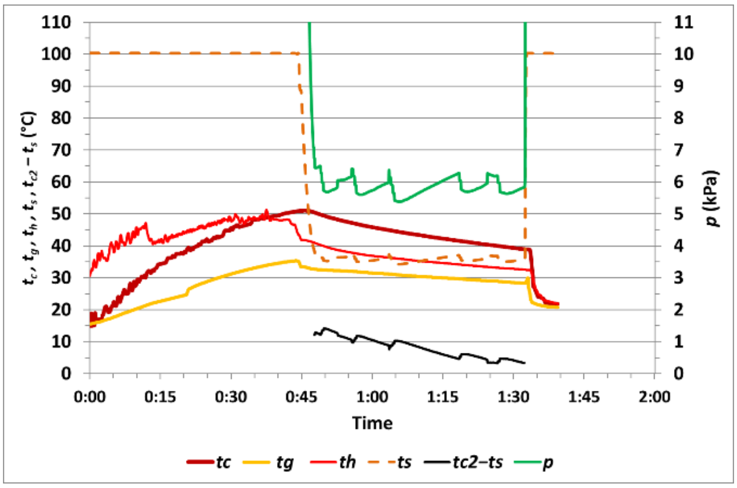

Figure 7. Measurement no. 2: Δw_c = 0.42% and $\Delta w_{c\ rel}$ = 4.00%.

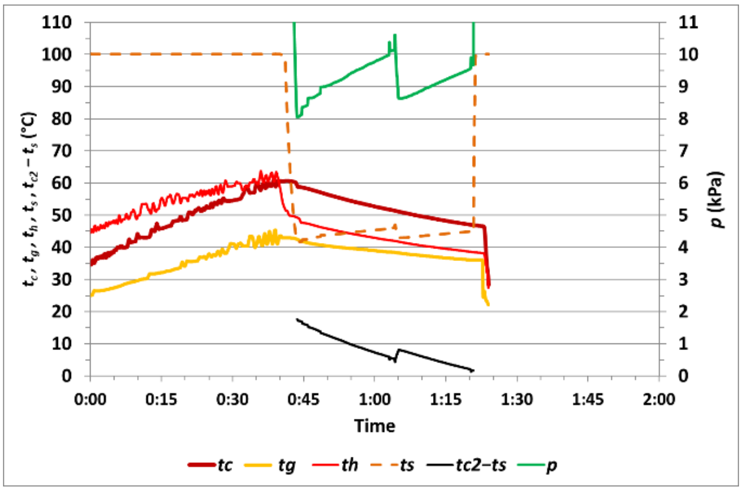

Figure 8. Measurement no. 4: Δw_c = 0.58% and $\Delta w_{c\ rel}$ = 5.55%.

During measurement no. 2, the corn sample was heated to a temperature t_{c1max} of 50.9 °C under an atmospheric pressure of 102.77 kPa in the vacuum chamber. Vacuum drying of the corn sample took place under a pressure $p_{2\ and\ vg}$ of 5.91 kPa. Evaporation of water from the corn kernels under reduced spiral power took 0:45 h, while the temperature t_{c2min} of the corn sample dropped to 38.9 °C, and the difference $(t_{c2}–t_s)_{min}$ between the corn temperature and water saturation temperature at pressure p_2 was 2.1 °C. By vacuum drying the corn sample, the moisture difference Δw_c was 0.42%, which corresponded to a relative moisture difference $\Delta w_{c\ rel}$ of 4.00%.

Measurement no. 4 of a corn sample took place under an atmospheric pressure p_1 of 101.95 kPa during its heating and under a pressure $p_{2\ and\ vg}$ of 9.19 kPa during vacuum drying. The temperature t_{c1max} at the end of heating rose to 60.3 °C, and, during vacuum drying, the temperature t_{c2min} was 46.9 °C. The temperature difference $(t_{c2}–t_s)_{min}$ was 1.7 °C. Vacuum drying took 0:37 h. During the corn drying process, the moisture difference Δw_c of the corn sample was 0.58%, and the relative moisture difference $\Delta w_{c\ rel}$ was 5.55%.

3.3. Effect of Heating Time on Reduction in Moisture during Evaporation of Water from Corn Sample

Measurements no. 12, no. 13 and no. 14 were carried out during atmospheric heating of the corn samples. During the evaporation of water from corn kernels, the pressure p_{2avg} in the vacuum chamber was in the range of 8.41–9.42 kPa. The increased power input of the coils compensated for the heat of evaporation of water from the grains during vacuum drying of the corn samples so the temperature t_{c2} of the corn samples changed minimally. The influence of the heating time τ_2 during the evaporation of water from the corn samples on the reduction in their moisture was investigated.

The heating time τ_2 during the vacuum drying of a corn sample for measurement no. 12 was 0:28 h (Figure 9). At a pressure p_{2avg} of 8.41 kPa, the temperature t_{c1max} of the sample was 60.0 °C at the end of heating, and t_{c2min} was 59.5 °C at the end of vacuum drying, while the temperature difference $(t_{c2}–t_s)_{min}$ was 16.9 °C. By vacuum drying the corn sample, the difference Δw_c between the moisture content w_{c1} of 8.86% at the beginning of the measurement and the moisture content w_{c3} of 8.56% after drying the sample on the sieve was 0.295%, which corresponded to a relative moisture difference $\Delta w_{c\ rel}$ of 3.335%.

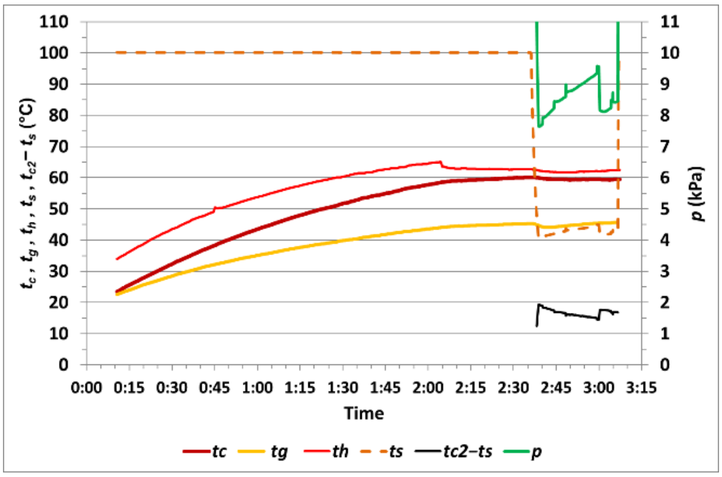

Figure 9. Measurement no. 12: Δw_c = 0.295% and $\Delta w_{c\ rel}$ = 3.335%.

Vacuum drying of a corn sample for measurement no. 13 took 0:42 h (Figure 10). The temperature of the corn sample during this phase was t_{c1max} = 60.5 °C at the end of heating and t_{c2min} = 59.6 °C at the end of vacuum drying, while the temperature difference $(t_{c2}–t_s)_{min}$ was 14.2 °C. The moisture difference Δw_c was 0.366%, and the relative moisture difference $\Delta w_{c\ rel}$ was 4.132%.

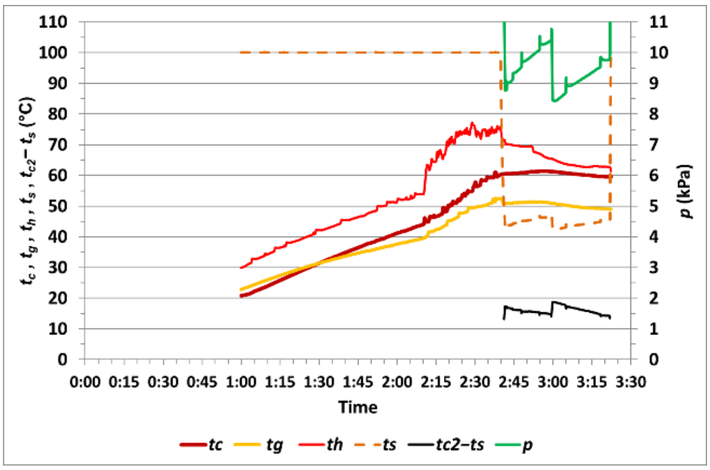

Figure 10. Measurement no. 13: Δw_c = 0.366% and $\Delta w_{c\ rel}$ = 4.132%.

During measurement no. 14, the heating time τ_2 during the vacuum drying of the corn sample was 0:58 h. The course of the measured values is shown in Figure 11. The pressure p_{2avg} reached a value of 8.73 kPa, and the measured temperatures of the corn sample were t_{c1max} 60.1 °C and t_{c2min} 62.8 °C, while the temperature difference $(t_{c2}–t_s)_{min}$ was 18.2 °C.

The resulting value of the moisture difference Δw_c was 0.373%, and the relative moisture difference $\Delta w_{c\ rel}$ was 4.212%.

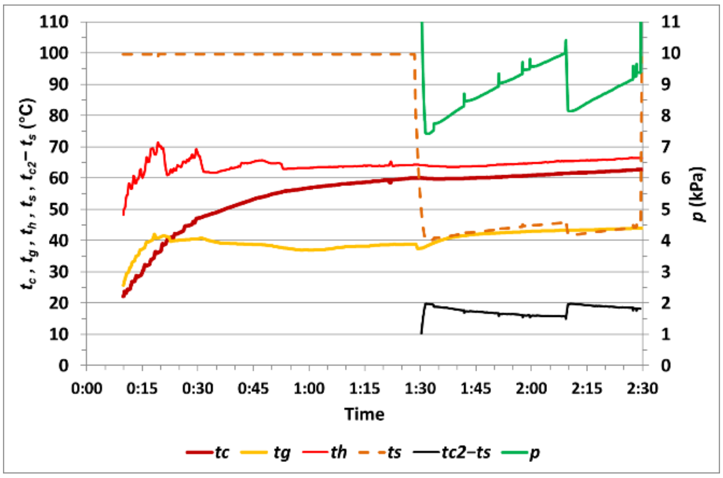

Figure 11. Measurement no. 14: Δw_c = 0.373% and Δw_{crel} = 4.212%.

During measurements no. 12, no. 13 and no. 14, the temperature difference t_{c2max} of the corn samples at the beginning of vacuum drying and t_{c2min} at the end of drying ranged from 0.9 °C (measurement no. 13) to −2.7 °C (measurement no. 14). For these measurements, the enthalpy change of steam corresponded to Δh_{eva} in the range of 2.0 kJ·kg^{-1} to −3.4 kJ·kg^{-1}. The average temperature $t_{c2\ avg}$ of the samples was in the range of 59.5 °C (measurement no. 12) to 61.0 °C (measurement no. 14). From the point of view of steam enthalpy change Δh_{eva} and temperature $t_{c2\ avg}$, vacuum drying of the corn samples took place under comparable conditions during these measurements. However, the most favorable conditions for the evaporation of water from corn grains were during measurement no. 14.

The moisture content of the corn samples from the initial w_{c1} value of 8.858% demonstrated the following course:

- During measurement no. 13 after a heating time τ_2 of 0:42 h of vacuum drying, the moisture content decreased to a value of w_{c3} = 8.492%, which corresponded to a moisture difference Δw_c of 0.366%, and relative moisture difference $\Delta w_{c\ rel}$ = 4.132%;
- During measurement no. 14 after a heating time τ_2 of 0:58 h of vacuum drying, the moisture content decreased to a value of w_{c3} = 8.485%, which corresponded to a moisture difference Δw_c of 0.373%, and relative moisture difference $\Delta w_{c\ rel}$ = 4.212%.

During measurement no. 14, the time τ_2 of vacuum drying was 0:16 h longer than during measurement no. 13, with a moisture difference Δw_c of 0.007% and a relative moisture difference $\Delta w_{c\ rel}$ of 0.080% between these measurements.

3.4. Effect of Number of Cycles of Water Evaporation on Reduction in Moisture

The effect of the number of cycles during the evaporation of water from the corn samples on the reduction in moisture was analyzed during the course and evaluation of measurements no. 5 and no. 9.

In these measurements, the corn samples were heated under atmospheric air pressure. During the time τ_2 of vacuum drying, the spiral power input was limited, and the pressure p_{2avg} was in the range of (8.31 ÷ 9.81) kPa.

The course of the measured values during measurement no. 5 with one cycle of vacuum drying is shown in Figure 12. The temperature t_{c1max} at the end of heating rose to 60.6 °C, and, during vacuum drying, the temperature t_{c2min} was 48.4 °C, while the temperature difference $(t_{c2}–t_s)_{min}$ was 0.6 °C. Vacuum drying of the corn sample took 0:34 h. The calculated difference in moisture Δw_c was 0.66%, and the relative moisture difference $\Delta w_{c\ rel}$ was 6.32%.

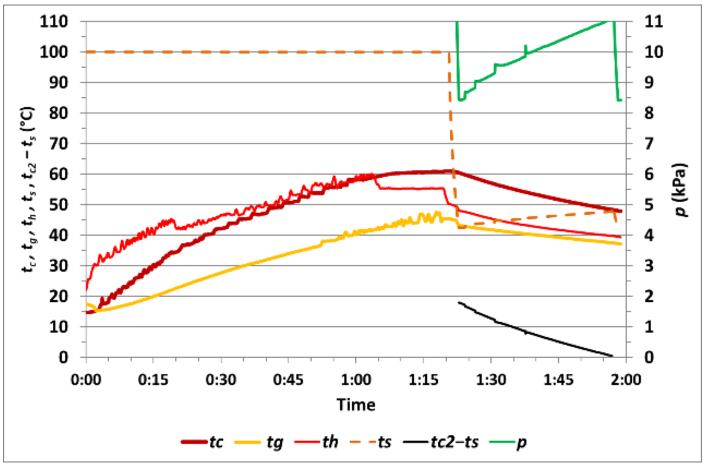

Figure 12. Measurement no. 5: Δw_c = 0.66% and $\Delta w_{c\ rel}$ = 6.32%.

Vacuum drying of a corn sample during measurement no. 9 took place over two cycles (Figure 13). After heating the corn sample at the beginning of the first cycle, the value of t_{c1max} reached 60.5 °C, and the value of t_{c2min} reached 48.7 °C, while the temperature difference $(t_{c2}–t_s)_{min}$ was 3.6 °C. After time τ_2 at 0:40 a.m., the sample was taken out of the vacuum chamber, and its weight m_{c2} was determined to be 1289.80 g. Based on the initial moisture content value w_{c1} and the subsequent moisture content values w_{c2} and w_{c3}, the moisture difference Δw_c was calculated to be 0.71%, and $\Delta w_{c\ rel}$ was 6.75%. The second drying cycle in the vacuum chamber began by heating the corn sample from a temperature t_{c1min} of 34.0 °C to a temperature t_{c1max} of 60.4 °C. Evaporation of water from the corn kernels took place for 0:46 h at a pressure p_{2avg} of 8.31 kPa. The corn sample was cooled to a temperature t_{c2min} of 48.6 °C, and the temperature difference $(t_{c2}–t_s)_{min}$ was 5.5 °C. From the determined weights m_{c1}, m_{c2} and m_{c3} of the corn sample and the moisture content values w_{c1}, w_{c2} and w_{c3}, the moisture difference Δw_c was calculated to be 0.56%, and the relative difference $\Delta w_{c\ rel}$ was calculated to be 5.76%. During the two cycles of vacuum drying, the initial mass m_{c1} of the sample decreased from a value of 1300 g to a mass m_{c3} of 1281.80 g after drying on a sieve. The difference Δw_c in the moisture content of the sample from w_{c1} at the beginning of the measurement to w_{c3} after drying the sample on a sieve corresponded to a change of 1.27%, and the relative moisture difference $\Delta w_{c\ rel}$ was 12.12%.

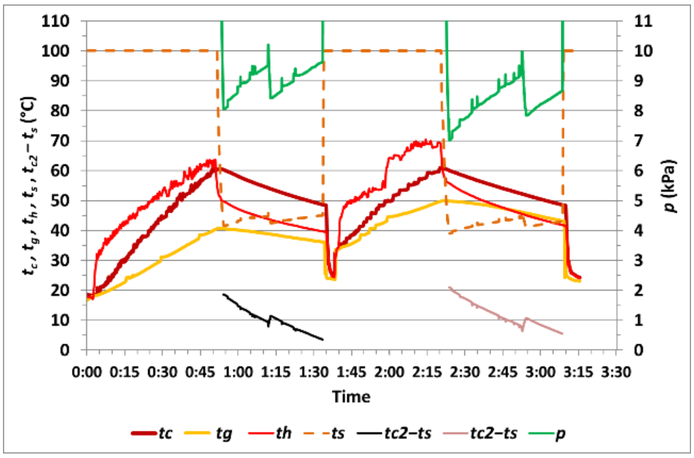

Figure 13. Measurement no. 9: Δw_c = 1.27% and $\Delta w_{c\ rel}$ = 12.12%.

4. Discussion

To optimize the process of vacuum drying corn, an experimental methodology was carried out using a simplified physical model of a vacuum dryer.

The courses of the temperature t_{ci} of the corn samples placed in a perforated basket, t_{gi} of the selected corn grain, t_{hi} of the electrically heated coils, t_s of water saturation, temperature difference t_{c2}–t_s during vacuum drying, pressure pi in the vacuum chamber during the heating of the corn samples and the evaporation of water from the grains during measurements no. 1 to no. 14 are listed in Table 1 and shown in Figures 6–15. The values of these variables were recorded in 5 s intervals.

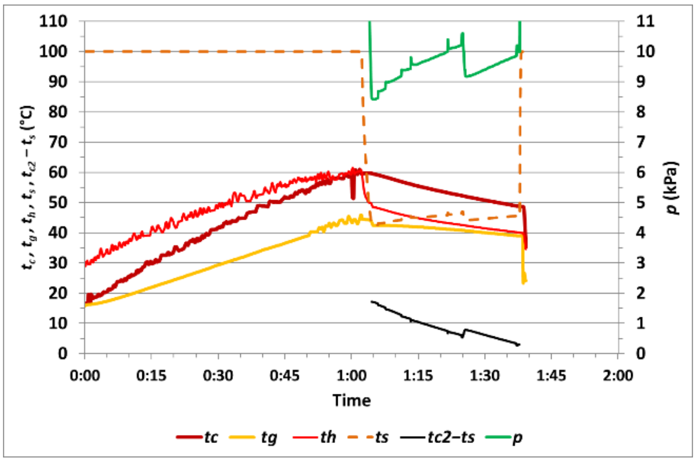

Figure 14. Measurement no. 6: Δw_c = 0.68% and $\Delta w_{c\ rel}$ = 6.48%.

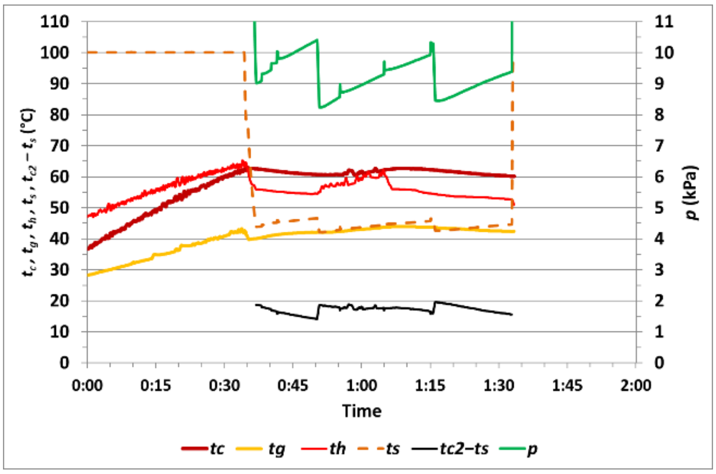

Figure 15. Measurement no. 8: Δw_c = 0.74% and $\Delta w_{c\ rel}$ = 7.09%.

During the dynamic events taking place under vacuum drying, it is possible to observe the temperature difference between the temperature t_{ci} of a corn sample and the temperature t_{gi} measured inside the grain. This difference, within the duration of the experiments, is caused by a delay in the penetration of the temperature wave propagated from the heat source through the environment into the grain of the dried material. The ability of the environment to spread heat also plays an important role. In cases where the speed of heat propagation through the environment is higher, it is possible to observe a smaller temperature difference and a better correlation of both processes.

4.1. Effect of Vacuum Chamber Pressure on Reduction in Moisture during Heating of Corn Sample

Let us briefly address the mechanism of heat propagation in the given environments of our study. The corn sample placed in the perforated basket contains a considerable intergranular volume due to the relatively large diameter of its grains. It is filled with the same substance as in the entire vacuum chamber. The heating process involves the transfer of heat from the heating source to the corn grains. Due to the shape of the grains, their mutual contact area is very small, which results in a reduction in the transmitted energy through heat conduction. A larger part of the grain surface is heated via thermal interaction with the surrounding environment. In the space between the grains, there is a combination of heat conduction and the flow of a low-pressure steam–gas mixture.

Under atmospheric pressure, there is a relatively high density of water vapor molecules in the space of the chamber and in the space between the grains, which is largely involved in heat transfer. In conditions where the pressure in the chamber is lower than the atmospheric pressure, there is a reduction in the number of these particles in such spaces, which also results in a reduced ability to transfer heat using the abovementioned mechanisms.

Heat transfer by radiation can take place between the heating medium and the heated material or between the grains themselves. However, due to the small temperature differences between individual grains, the amount of energy transferred by radiation is minimal.

From the experimentally determined values of moisture difference Δw_c and relative moisture difference $\Delta w_{c\ rel}$, and the above brief explanation of heat transfer from the electric coils to the corn kernels in the vacuum chamber, it follows that it is more appropriate to heat a corn sample under atmospheric pressure $p_{1.}$

4.2. Effect of Vacuum Chamber Pressure on Reduction in Moisture during Evaporation of Water from Corn Sample

During measurements no. 2 and no. 4, the influence of the absolute pressure level $p_{2\ avg}$ on the vacuum drying process can be observed. Keeping the conditions as similar as possible in terms of the temperature difference between the grain temperature and the water saturation temperature, the effect can be attributed to the change in the value of the vaporization heat of water:

$$\Delta h = h''\left(p_{2\ avg}\right) - h'\left(p_{2\ avg}\right) \tag{5}$$

where $h''\left(p_{2\ avg}\right)$ represents the enthalpy of saturated steam, and $h'\left(p_{2\ avg}\right)$ is the enthalpy of saturated water at pressure $p_{2\ avg}$.

During measurement no. 2 (Figure 7), the pressure p_{2avg} of 5.91 kPa corresponds to a saturation temperature t_s (p_{2avg}) of 35.9 °C and a vapor heat $\Delta h2$ of 415.8 kJ·kg^{-1}. The pressure p_{2avg} of 9.19 kPa during measurement no. 4 (Figure 8) corresponds to a saturation temperature t_s (p_{2avg}) of 44.2 °C and a vapor heat Δh of 2396.0 kJ·kg^{-1}. The relative difference in the values of vaporization heat of measurements no. 4 and no. 2 is 0.82%. The value of the heat of vaporization Δh decreases with an increase in pressure, which results in an increase in the amount of evaporated water while maintaining the same amount of accumulated energy in the grains or the same amount of heat supplied by the spiral coils.

From the experimentally determined values of moisture difference Δw_c and relative moisture difference $\Delta w_{c\ rel}$, it follows that it is more appropriate to vacuum dry a corn sample under a p_{c2avg} range of 9–10 kPa, with the most appropriate pressure being around 6 kPa.

4.3. Effect of Controlling the Power Input of Coils on Reduction in Moisture during the Evaporation of Water from Corn Kernels

The effect of heating intensity during the evaporation of water from corn kernels on the reduction in maize moisture content was investigated. During measurement no. 6, the power consumption of the coils was reduced (Figure 14). At a pressure p_{2avg} of 9.51 kPa, the temperature t_{c1max} of the sample dropped from a value of 59.8 °C at the end of vacuum drying to a temperature t_{c2min} of 48.8 °C, while the temperature difference $(t_{c2}–t_s)_{min}$ was 3.0 °C. Evaporation of water from the corn kernels took 0:33 h. By vacuum drying the corn sample, the difference in moisture Δw_c between the value w_{c1} at the beginning of the measurement and the value w_{c3} after drying the sample on the sieve was 0.68%, which corresponded to a relative moisture difference $\Delta w_{c\ rel}$ of 6.48%.

Measurement no. 8 during the vacuum drying of a corn sample took 0:56 h at a pressure p_{2avg} of 9.26 kPa (Figure 15). The spiral coils compensated for the heat of evaporation of water from the grains with increased power during the vacuum drying process of the corn sample. The temperature t_{c2} of the corn sample varied from 62.6 °C to 60.2 °C, while the mean temperature t_{c2avg} was 61.5 °C. The difference (t_{c2}–t_s) between the corn sample temperature and water saturation temperature was 15.6 °C. During the corn drying process, the moisture difference Δw_c of the corn sample was 0.74%, and the relative moisture difference $\Delta w_{c\ rel}$ was 7.09%.

Let us compare the enthalpy change of steam during the vacuum drying of the corn samples in measurements no. 6 and no. 8. The calculation was as follows:

$$\Delta h_{eva} = h_{steam}(p_{2\ avg},\ t_{c2\ max}) - h_{steam}(p_{2\ avg},\ t_{c2\ min}) \tag{6}$$

Vacuum drying during measurement no. 6 took place at a reduced spiral power. At a medium pressure $p_{2\ avg}$ in the vacuum chamber, the cooling of the corn sample from the temperature $t_{c2\ max}$ to $t_{c2\ min}$ by 11.0 °C corresponded to a decrease in the enthalpy change of steam Δh_{eva} of 9.6 kJ·kg^{-1}. During measurement no. 8, the spiral coils heated the corn sample so that the temperature t_{c2} changed as little as possible (by 2.4 °C). The corresponding decrease in the enthalpy change of steam Δh_{eva} was 2.6 kJ·kg^{-1}. The dry matter of corn grains was cooled less, and water evaporation took place under more favorable conditions.

Heating a corn sample during the phase of vacuum drying has a favorable effect on the moisture difference Δw_c and the relative moisture difference $\Delta w_{c\ rel}$ of the corn sample.

4.4. Effect of Heating Time on Reduction in Moisture during Evaporation of Water from Corn Sample

Based on the results of measurements no. 12, no. 13 and no. 14, which were experimentally determined during the heating time τ_2 during the evaporation of water from the corn sample to reduce its moisture, and from the point of view of the values of moisture difference Δw_c and $\Delta w_{c\ rel}$ and the energy requirement of heating the dry matter of a corn sample, it is recommended that the τ_2 phase of vacuum drying of a corn sample lasts for a duration of 0:40–0:45 h.

4.5. Effect of Number of Cycles of Water Evaporation on Reduction in Corn Moisture

When vacuum drying over two cycles, the difference in the moisture content of the corn sample (Δw_c) is reduced by a factor of 1.92 compared to drying in one cycle (measurement no. 5). For measurement no. 9 with two cycles of vacuum drying of a corn sample, let us compare the moisture reduction $\Delta w_{c1.\ cyc}$ in the first cycle with the moisture reduction $\Delta w_{c2\ cyc}$ in the second cycle. The moisture reduction ratio $\frac{\Delta w_{c\ 1.\ cyc}}{\Delta w_{c\ 2\ cyc}}$ was 1.29 so, in the first cycle, the moisture difference Δw_c was reduced 1.29 times more than in the second cycle.

Measurement no. 9 was affected by the selection of the corn sample from the vacuum chamber due to the need to determine the mass m_{c2} of the sample after the first cycle. Without selecting the sample from the vacuum chamber, the heat consumption for heating the corn sample and the heating time would be reduced.

Vacuum drying a corn sample over two cycles can be recommended if a moisture reduction Δw_c of approximately twice that obtained when drying in one cycle is desired.

5. Conclusions

For the individual measurements, the initial moisture content of the corn samples was different. The reason was different collection dates. The initial moisture content ranged from 10.49% to 8.86%. Considering the preservation of the nutritional quality of dried corn, the maximum temperature t_{cmax} = 63 °C was set for all phases of vacuum drying. The temperature during drying, t_{c2}, changed due to the evaporation of moisture and the current performance of the coils. With reduced spiral power, vacuum drying ended if the difference between the corn temperature t_{c2min} and the water saturation temperature $t_{s(p2)}$ was less than or equal to 0.5–5.5 °C. For the drying process, it is necessary that the water saturation temperature is lower than the current temperature of the corn sample.

Considering this difference in the given interval and the maximum temperature of 63 °C, it is necessary to maintain the pressure in the vacuum chamber at a level of 10 kPa. If, during the drying of corn, the heat supplied by the spiral coils is compensated by the vapor heat of evaporated water (the temperature does not change during this process), a higher saturation temperature can be chosen, e.g., $t_{s(p2)}$ = 58.0 °C. This temperature corresponds to a saturation pressure $p_{s(t2)}$ = 18.17 kPa and a heat of vaporization $\Delta h = 2362.6$ kJ·kg^{-1}. Under these conditions, the heat of vaporization is 1.23% less than the heat of vaporization at a pressure of 10 kPa. This has the effect of reducing the energy consumption of the drying process.

Based on the obtained data, it can be concluded that the following procedures are appropriate to dry corn with minimal energy consumption:

- Heat the corn sample at a higher pressure value in the vacuum chamber using better heat transfer for more intense heat convection;
- Carry out the drying phase in the pressure range of 9–10 kPa, and, when drying at a lower pressure, a higher moisture content of corn is achieved;
- Continuously heat the corn sample during the entire drying phase so that the temperature of the corn sample changes minimally;
- Choose a heating time in the range of 40–45 min and a heating intensity corresponding to the rate of heat transfer in the given environment;
- Due to the dynamics of the drying process, it is advantageous to carry out the drying process with a low intensity over several cycles.

In this study, individual recommendations were applied in the construction and operation process design of a prototype mobile vacuum dryer intended for drying corn. The measurements show the advantage of drying under a higher pressure, i.e., 9–10 kPa. The maximum pressure is limited by the maximum temperature under which maize can be heated while still maintaining its nutritional content. These values are also used for the strength calculation of the proposed drying chamber. With multiple drying cycles, thermal energy capture can be realized, and the captured energy can then be reused. This includes the use of condensation heat from the previous cycle for heating during the subsequent cycle. However, the temperature level needs to be adjusted. Verification of the recommendations and possible further optimization of the drying process during the test operation of the prototype vacuum dryer are necessary.

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