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Expert Paper

ACTIVE VENTILATION OF GRAIN IN STORAGE
AKTIVNA VENTILACIJA USKLADIŠTENOG ZRNA

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INTRODUCTION

Storing grain in silos cells and floor storage does not end its life cycle. Biochemical processes are active in the grain, most notably aerobic respiration and anaerobic respiration, which contribute to increased moisture and temperature in stored grain. Many factors contribute to the intensity of respiration; temperatures of the grain, type of grain, presence of damage or impurities, presence of grain pests, etc. In most cases, we are unable to resolve these issues without moving (elevating) the grain. However, there is one important factor that we can manage in the storage, the temperature of the stored grain and the relative air humidity in the intergranular space. When the temperature of stored grain is lowered the intensity of respiration is lowered as well. Depending on the quality of the equipment lowering the temperature in the grain mound can be accomplished in three ways:

- “elevation”,
- cooling the grain with cooled air (granifrigor device)
- cooling the grain with surrounding air – active ventilation

Cooling the grain with surrounding air (active ventilation) is a technically adequate and investment-acceptable method used by most silos, especially when compared to cooling the grain with cooled air (granifrigor device). With adequate and timely utilization of the active ventilation system, it is possible to achieve an effect that mimics that of a grainfrigor device, but with lower exploitation and investment costs.

In practice, there is a fear of making grain wet when using the active ventilation system due to the variable temperatures and humidity of the surrounding air. In this paper, a theoretical and practical explanation of the interaction between the ambient air used for active ventilation and the stored grain will be presented. By understanding the interaction between air and the grain the use of active ventilation becomes simple. Furthermore, attention will be paid to the necessary technical capacities of the systems for active ventilation and the exploitation costs.

GRAIN MOISTURE EQUILIBRIUM

Knowledge of the regularity of moisture and heat exchange between the grain and the surrounding air is the basis for the adequate use of the active ventilation system and is directly connected to grain moisture equilibrium. Grain moisture equilibrium is a state of thermal and mechanical balance between the grain and the air that surrounds it and is dependent on the following:

- the relative air humidity surrounding the grain
- the air temperature
- the temperature of the grain
- the static air pressure surrounding the grain
- the chemical composition of the grain (the proportionate values of protein, starch, and oil) and
- the type of grain (sort, hybrid)

The basic driving force in moisture exchange between the grain and the air that surrounds it is the value of the partial pressure of water vapors in the grain and air. When the pressure is in equilibrium there is no exchange of moisture; when the partial pressure of water vapors in the grain is higher than in the air, water vapors transfer from the grain to the air in a process of drying (desorption). When the situation is reversed and the partial pressure of water vapors is lower in the grain than in the air, the molecules of water vapors are transferred from the air to the grain and the grain becomes wet (sorption).

The partial pressure of water vapors in the air depends on the absolute air humidity. The higher the absolute air humidity is, the greater the partial pressure of water vapors in the air. Instead of the absolute air humidity, the grain moisture equilibrium is presented in the tables and diagrams dependent on the relative air humidity, the air temperature, and the temperature of the grain. Relative air humidity, as the name suggests, presents the relative (dependent) value attributed to the air humidity that depends on the temperature and the absolute air humidity. In general, for the same air temperature when absolute air humidity is increased (by adding water vapors) the relative air humidity increases, i.e. the partial pressure of water vapors increases. Vice versa, with a decrease in absolute air humidity, for the same temperature (by removing water vapors) the values of relative air humidity decrease, i.e. the partial water vapor pressure decreases. Only by increasing air temperature, without adding water vapor, can we lower the relative air humidity, but this does not change its absolute humidity. Similarly, when the air temperature is lowered, relative humidity increases without a change in the absolute humidity, i.e. it does not affect the partial pressure of water vapor. These relations can lead to confusion if only relative air humidity is observed. In some instances of air state, air with higher relative humidity and a lower temperature is drier than the air with lower relative humidity and a higher temperature. For example, air with a temperature of 25ºC and a relative humidity of 50% has an absolute humidity value of 0,009879 $kg_w/kg_{s.v.}$ and a partial water vapor pressure of 1563,43 Pa, while the air with a temperature of 15ºC and a relative humidity of 90% has an absolute humidity value of 0,009563 $kg_w/kg_{s.v}$ and a partial water vapor pressure of 1514,17 Pa. Therefore, air with a higher temperature and a lower relative humidity has a higher potential of wetting the grain if the partial water vapor pressure in the grain is lower than 1563,43 Pa. It is important, when assessing the ventilation air conditions, to use both values, the temperature and the relative humidity, in order to calculate the values of absolute air humidity which is related to the partial water vapor pressure in the air. Values for the absolute air humidity and the partial water vapor pressure are obtained through Mollier’s diagram for humid air.

Different types of grain (wheat, maize, sunflower) have different moisture equilibriums under the same conditions as the surrounding air. These differences occur due to the variations in the chemical content. Grains of wheat and maize are rich in starch which has a higher capacity for binding higher levels of moisture when compared to soybean and sunflower which predominantly consist of oil and protein. Therefore, the moisture equilibrium in wheat and maize is higher than in oilseeds, even in equal air conditions (tables 1 to 4). The differences in the chemical structure between the same types of grain also lead to a deviation in moisture equilibrium values in grain varieties and hybrids. Therefore, sunflower hybrids with a higher oil content will have a lesser moisture equilibrium under the same air conditions when compared to hybrids with a higher oil content. These deviations can be from 0.1% to 0.9%. With this in mind, the data, concerning moisture equilibrium, in the tables taken from source literature for all types of grain, should be used with care and caution. It is essential to take note when using older sources due to the introduction of new hybrids and varieties with a changed chemical structure and an increased content of oil, protein, or other components in the grain.

The values for the moisture equilibrium for a specific material, according to the given analytical dependence, are obtained experimentally. The results are graphically represented by isotherms in (%) i $_{e}$(%) coordinates. A typical shape of the isotherms is a Latin letter "S" and has a functional dependency of $_{e}$ = (t).

The state of equilibrium in the system that consists of material and humid air can be accomplished in two ways:

- through drying (desorption) of the material
-through wetting (sorption) of the material.

Isotherms for sorption and desorption in capillary-porous-colloid materials do not match, except in the values for relative air humidity close to 100% and 0% (Image 1). This occurrence of hysteresis is typical in objects with a colloid structure, while it does not appear in capillary-porous objects. Sorption allows for lower moisture values than desorption, under the same temperature conditions and air humidity, when dealing with capillary-porous colloid objects. Isotherms for sorption are obtained by static wetting of the grain that was first dried completely creating an entirely dry matter where, during the drying process, the physical structure of the grain and the plasmolysis of the cells in certain parts were breached (they are unable to absorb moisture). On the other hand, with desorption isotherms, the grain is dried from its starting moisture content to the moisture equilibrium in known air states, temperatures, and relative moisture. The beneficial data is the one obtained through desorption isotherms.

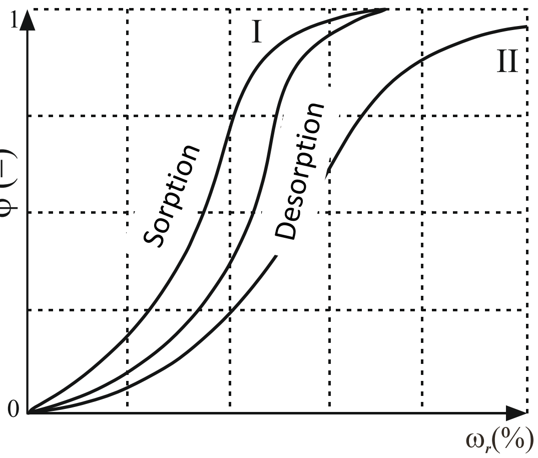

Fig. 1. A typical shape of isotherms for sorption and desorption (I- capillary-porose-colloid bodies, II – capillary–porose bodies)

GRAIN RESPIRATION

When planning a system of active ventilation, the aerobic and anaerobic respiration of the stored grain should be taken into consideration. During the process of grain respiration, there is an increase in temperature and moisture content at the expense of a decrease in the dry matter of the grain. The goal of active ventilation is to, by airing the stored grain, bring this process down to an acceptable level. Due to the increase of moisture content in the stored grain that is followed by an increase in its temperature the partial pressure of the water vapor in the grain is also increased and the molecules of water vapor are released into the space between the grains. This way the relative air humidity in the area around the grain is increased and when it reaches values over 65% conditions are created for the creation of mold and other storage vermin while the process of self-warming is hastened. By using the table of moisture equilibrium based on the measured temperature of the grain in storage, we can approximately determine the change in moisture, with the data that every degree the temperature of grain is increased, due to respiration, the moisture content increases by 0.04 - 0.6 %/ºC in oilseeds and by 0.05 - 0.1%/ºC in cereal. Self-warming of grain in storage when observed over the whole volume, happens unequally. In certain zones of the stored grain, the conditions for respiration are more suitable, therefore, the intensity of water-vapor production is greater.

DETERMINING THE WORKING CONDITIONS FOR ACTIVE VENTILATION SYSTEMS

Turning on the active ventilation system depends on the temperature of the grain in the storage, the relative air humidity in the space between the grain, and the state of the ambient air (the temperature and the relative air humidity). The basic condition for the active ventilation system to turn on is that the temperature of the ambient air reaches levels lower than the temperature of the stored grain. When the basic condition is fulfilled, nomograms are used to air out the grain (Themir's diagram) or the tables for the grain moisture equilibrium. A nomogram by Themir is essentially a Molier's diagram of air humidity and its use is somewhat more complex than the tables and will not be included in this research.

Using a table to determine the suitable conditions is simpler for the majority of users than the use of nomograms. Table 1 shows the data on the moisture equilibrium of hard wheat based on the temperatures of the grain and air together with the relative air humidity. The white "zone", as seen in the table, represents the safe zone for using active ventilation, which means that the conditions of the air temperature and relative humidity are suitable for the moisture of hard wheat at 13%. To the left of the safe zone, the conditions will cause the drying of the grain by 13%, and to the right of the safe zone, the air conditions will cause the wetting of the grain by 13%. By looking at the table we can determine that the interesting values for active grain ventilation include temperatures of air lower than 30ºC and a relative air humidity ranging from 45% to 60%.

Table 2 represents the data on moisture equilibrium for maize based on the temperature of the grain/air and the relative air humidity. The white "zone", as seen in the table, represents the safe zone for using active ventilation, which means that the conditions of the air temperature and relative humidity are suitable for the moisture of maize 14%. To the left of the safe zone, the conditions will cause the drying of the grain by 14%, and to the right of the safe zone, the air conditions will cause the wetting of the grain by 14%. By looking at the table we can determine that the interesting values for active grain ventilation include temperatures of air lower than 25ºC and a relative air humidity ranging from 55% to 65%.

Table 1. Moisture equilibrium for the grain of hard wheat based on the grain temperature and the relative air humidity (-Zone of drying grain; -Zone of wetting grain) (ASAE, 1996)

Grain temp. (ºC)	Relative air humidity (%)															
	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95
0	8,7	9,6	10,5	11,3	12,1	12,8	13,6	14,3	15,1	15,8	16,4	17,5	18,5	16,6	21,0	23,0
5	8,4	9,3	10,1	10,9	11,6	12,3	13,1	13,8	14,5	15,3	16,1	17,9	17,9	19,0	20,3	22,1
10	8,2	9,0	9,8	10,6	11,3	12,0	12,7	13,4	14,2	14,9	15,7	16,5	17,4	18,5	19,8	21,7
15	7,9	8,7	9,5	10,3	11,0	11,7	12,3	13,0	13,7	14,4	14,2	16,0	16,9	17,9	19,2	21,1
20	7,7	8,5	9,3	10	10,7	11,4	12,1	12,6	13,4	14,1	14,9	15,7	16,6	17,6	18,6	20,6
25	7,5	8,3	9,0	9,7	10,4	11,1	11,7	12,4	13,1	13,8	14,5	15,3	16,1	17,1	18,4	20,2
30	7,4	8,1	8,9	9,6	10,2	10,9	11,5	12,1	12,8	13,4	14,2	15,9	15,8	16,7	18,0	19,7
35	7,2	7,9	8,7	9,3	10,0	10,6	11,2	11,9	12,5	13,2	13,9	14,6	15,5	16,4	17,6	19,4

Table 2. Moisture equilibrium for grain of maize based on the grain temperature and the relative air humidity (-Zone of drying grain; -Zone of wetting grain) (ASAE, 1996)

Grain temp. (ºC)	Relative air humidity (%)															
	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95
0	7,7	8,7	9,7	10,6	11,5	12,4	13,2	14,2	15,0	16,0	17,0	18,1	19,3	21,7	22,5	25,0
5	7,3	8,2	9,2	10,1	11,0	11,8	12,6	13,5	14,4	15,3	16,2	17,4	18,6	20,0	21,6	24,1
10	7,0	8,0	8,8	9,7	10,5	11,3	12,2	13,0	13,9	14,8	15,7	16,7	17,9	19,2	20,9	23,3
15	6,7	7,6	8,5	9,3	10,1	10,9	11,7	12,5	13,3	14,2	15,1	16,1	17,2	18,5	20,1	22,5
20	6,5	7,4	8,2	9,0	9,8	10,6	11,3	12,1	12,9	13,7	14,6	15,6	16,7	17,9	19,5	21,8
25	6,2	7,1	7,9	8,7	9,4	10,2	10,9	11,7	12,5	13,3	14,1	15,1	16,1	17,3	18,6	21,2
30	6,1	6,9	7,7	8,4	9,2	9,9	10,6	11,4	12,1	13,0	13,8	14,7	15,8	17,0	18,4	20,6
35	5,9	6,7	7,4	8,2	8,9	9,6	10,3	11,0	11,8	12,5	13,4	14,3	15,3	16,5	17,9	20,1

Table 3 represents the data on moisture equilibrium for soybeans based on the temperature of the grain and the relative air humidity. Soybean is stored with moisture of 12% or even lower if that is the demand of the soybean processing plant. Such low moisture of soybean causes issues for the work with active ventilation due to the low relative air humidity. The white "zone", as seen in the table, represents the safe zone for using active ventilation, which means that the conditions of the air temperature and relative humidity are suitable for the moisture of soybean 12%. To the left of the safe zone, the conditions will cause the drying of the soybean at 12%, and to the right of the safe zone, the air conditions will cause the wetting of the soybean at 12%. By looking at the table we can determine that the interesting values for active grain ventilation include temperatures of air lower than 20ºC and a relative air humidity ranging from 60% to 65%.

Table 3. Moisture equilibrium for soybean based on the grain temperature and the relative air humidity (-Zone of drying grain; -Zone of wetting grain) (ASAE, 1996)

Grain temp. (ºC)	Relative air humidity (%)															
	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95
0	3,9	4,8	5,6	6,5	7,4	8,3	9,3	10,4	11,4	12,6	14,0	15,3	17,0	19,0	21,6	25,4
5	3,8	4,6	5,5	6,3	7,2	8,1	9,1	10,1	11,1	12,3	13,6	15,0	16,6	18,6	21,1	24,9
10	3,7	4,5	5,3	6,1	7,0	7,9	8,8	9,8	10,8	11,9	13,2	14,6	16,2	18,1	20,6	24,3
15	3,6	4,3	5,1	5,9	6,8	7,6	8,6	9,5	10,5	11,6	12,8	14,2	15,7	17,6	20,1	23,7
20	3,5	4,3	5,0	5,8	6,5	7,4	8,3	9,3	10,3	11,4	12,6	13,9	15,4	17,3	19,7	23,3
25	3,4	4,1	4,9	5,6	6,4	7,2	8,1	9,0	10,0	11,0	12,2	13,6	15,0	16,8	19,1	22,7
30	3,3	4,0	4,8	5,6	6,3	7,1	8,0	8,9	9,9	10,9	12,0	13,3	14,8	16,6	18,9	22,5
35	3,2	3,9	4,7	5,4	6,2	7,0	7,8	8,7	9,6	10,6	11,7	13,0	14,5	16,2	18,5	22,0

Table 4 represents the data on moisture equilibrium for sunflower seeds based on the temperature of the grain and the relative air humidity. Sunflower seed is stored with a moisture of 7%. Such low moisture of sunflower seed causes issues for the work with active ventilation due to the low relative air humidity. The white "zone", as seen in the table, represents the safe zone for using active ventilation, which means that the conditions of the air temperature and relative humidity are suitable for the moisture of sunflower seed of 7%. To the left of the safe zone, the conditions will cause drying of the sunflower seed 7%, and to the right of the safe zone, the air conditions will cause wetting of the sunflower seed 7%. By looking at the table we can determine that the interesting values for active ventilation of sunflower seed include temperatures of air lower than 20ºC and a relative air humidity ranging from 40% to 65%.

Table 4. Moisture equilibrium for sunflower seed based on the grain temperature and the relative air humidity (-Zone of drying grain; -Zone of wetting grain) (ASAE, 1996)

Grain temp. (ºC)	Relative air humidity (%)															
	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95
0	4,8	5,4	5,9	6,4	6,8	7,3	7,7	8,2	8,6	9,1	9,6	10,2	10,8	11,5	12,4	13,7
5	4,6	5,1	5,6	6,1	6,5	7,0	7,4	7,8	8,3	8,7	9,2	9,7	10,3	11,0	11,9	13,1
10	4,5	4,9	5,4	5,8	6,3	6,7	7,1	7,5	8,0	8,4	8,9	9,4	10,0	10,6	11,5	12,7
15	4,3	4,8	5,2	5,6	6,1	6,5	6,9	7,3	7,7	8,1	8,6	9,1	9,6	10,3	11,1	12,3
20	4,2	4,6	5,0	5,5	5,9	6,2	6,6	7,0	7,4	7,9	8,3	8,8	9,3	9,9	10,7	11,9
25	4,0	4,5	4,9	5,3	5,7	6,1	6,4	6,8	7,2	7,6	8,1	8,5	9,0	9,7	10,4	11,5
30	4,0	4,4	4,8	5,2	5,6	6,0	6,3	6,7	7,1	7,5	7,9	8,4	8,9	9,5	10,3	11,4
35	3,9	4,3	4,7	5,1	5,4	5,8	6,2	6,5	6,9	7,3	7,7	8,2	8,7	9,3	10,0	11,1

By analyzing tables 1-4 there is a markedly "narrow" safe zone for active ventilation due to relative air humidity for all types of grain. Table 5 shows the mean temperatures of ambient air and the relative moisture content with the medium, maximum, and minimal values for all the months in 2023. After analyzing the table it is evident that the medium day temperatures are suitable in most months, but that relative moisture content varies in 24h. Therefore, active ventilation can not be used for 24 hours and is only turned on when the conditions of temperature and relative moisture of the ambient air are met.

Table 5. Mean temperature and air humidity by moths in 2023 measured at the meteorological measuring station at the Surčin airport (https://www.wunderground.com)

Month	Air temperature (ºC)		Relative air humidity (%)		Month	Air temperature (ºC)		Relative air humidity (%)	
January	12,02	16,0	85,37	96,8	Jully	21,03	34,0	62,56	88,53
		10,0		68,83			13,0		39,57
February	11,19	19,0	72,87	91,32	August	23,99	37,0	64,92	90,5
		-7,0		49,39			13,0		40,7
March	15,73	25,0	66,74	87,57	September	28,1	33,0	62,36	88,92
		-3,0		45,78			12,0		39,46
April	10,58	23,0	71,34	93,53	October	17,3	30,0	65,45	90,0
		0		48,39			3,0		41,92
May	26	26,0	91,17	71,68	November	8,93	23,0	77,18	90,64
		5,0		52,67			-2		56,35
June	21,03	34,0	73,6	94,5	December	5,82	22,0	79,15	93,67
		13,0		52,28			-5,0		61,14

For further more in-depth analysis of daily changes in air conditions and the representation of examples of proper determination of work conditions for the application of an active ventilation system, table 6 shows daily temperatures and relative air humidity on the day of 20th September 2023.

Table 6. Temperatures and relative air humidity on 20. September. 2023, measured at the meteorological station at the Surčin airport (https://www.wunderground.com)

Time (h)	Air temperature (ºC)	Relative air humidity (%)	Time (h)	Air temperature (ºC)	Relative air humidity (%)
0:00	12	42	12:00	15	78
1:00	13	44	13:00	15	83
2:00	13	42	14:00	14	82
3:00	13	39	15:00	14	88
4:00	12	37	16:00	14	88
5:00	12	37	17:00	14	88
6:00	12	42	18:00	13	88
7:00	12	44	19:00	14	88
8:00	13	50	20:00	15	83
9:00	14	57	21:00	15	68
10:00	14	60	22:00	15	61
11:00	14	57	23:00	14	50

Considering the fact that in September wheat and sunflower seeds were stored, ambient air can be used for active ventilation. The example of wheat and sunflower seeds will be used to explain the way to determine the conditions for proper work of an active ventilation system.

Example for the wheat grain: wheat grain is stored in a silo with a starting temperature of 30ºC and medium moisture content during storing of 13%. During the storing time, its temperature has increased to 35ºC. Due to the increase in temperature of the grain for t = 5ºC, as a result of respiration, the grain moisture increased by 5ºC x 0,1%/ºC= 0,5% and is now 13.5%. According to Table 1, the moisture of the grain of 13.5% relates to the relative air humidity in the intergranular area of 67%. It is necessary to cool off the grain by turning on the active ventilation system. Firstly, we determine the grain temperature and the moisture that we want to achieve by using Table 1, in this example it is 15ºC and 55%. The system for active ventilation will turn on during the day when temperatures and relative humidity of the surrounding air reach values lower than the set values (15ºC and 55%), and turn off when the medium temperature of the surrounding air and the medium relative air humidity of the air used for active ventilation exceed the set values (15ºC and 55%). It will turn on again when the set conditions are met. When the desired medium temperature of the grain in the silo is achieved, the system will turn off entirely. According to the data from Table 6. the system for active ventilation on the 20th of September had reached the conditions of ambient air from 18h, during which the medium air temperature was 13.35ºC and the relative air humidity was 55.16%. The system will turn on and off until the desired temperature of the grain in silo is reached.

Example for the sunflower seed: sunflower seed was stored in a silo during August, with a medium temperature of 30ºC and a medium humidity of 7%. The grain did not warm up in the silo, but an attempt was made to use the lower temperature of the surrounding air in order to cool it and by doing that lower the grain respiration and the creation of fatty acids in the sunflower seed. According to Table 4, the humidity of the sunflower seed of 7% and the temperature of 30ºC relates to a relative air humidity of ≈58%. By using Table 4, we can determine the desired grain temperature and the humidity we want to achieve by the use of active ventilation; for this example, a medium grain temperature of 20ºC was chosen for the entire silo unit, and the medium grain humidity of 7 %, these parameters correlate with a relative air humidity of 55%. The system for active ventilation will turn on when the temperature and the relative humidity of the surrounding air and the medium relative air humidity which is used for ventilation is higher than the chosen values (≤20ºC, ≤55%). Also, the system will turn off when the medium temperature of the surrounding air and the medium relative air humidity used for ventilation are higher than the chosen values (≥20ºC, ≥55%), and turn on again when the set criteria are met. When the desired medium temperature of the grain in the silo is reached the system will turn off. According to the data in Table 6, the active ventilation system, on the 20th of September, had met the work conditions from 17h when the medium air temperature used to cool the grain was 13,35ºC and the medium relative air humidity of 53,23%.

COMPONENTS OF THE ACTIVE VENTILATION SYSTEM

The active ventilation system consists of a medium pressure centrifugal fan, an electromotor with a frequency regulator, an intake pipe, a pressure pipe, a silo cell, or a floor storage able to use active ventilation and vents to release air. In order to efficiently and adequately use the favorable conditions of ambient air it is important that the system is automated. In the part of automatization, sensors are needed for measuring temperature and the relative humidity of ambient air. It is enough to have one measuring location for the entire silos, a programmable controller or PLC/SCADA, relays for turning the fans on and off, and power cables.

In different sources, it is possible to find various approaches to determining the flow of fans in the active ventilation system. Airflow in a fan is calculated, not taken. It is based on the recommended medium air speed in a horizontal plane in front of the grain layer (apparent speed), measured from 0,025 m/s to 0,05 m/s. It must be taken into account that resistance to airflow (linear and local) grows with the square of the speed, and with it, the consumption of energy needed to power the fan motors grows as well. It is needed to choose the optimal apparent speed. Greater air speeds will cause a greater consumption of electrical energy that does not correlate with the speed of lowering the temperature of the grain in storage, therefore the prices of airing will be too high. For higher layers of the grain (>10 m) the lower border is adopted (0,025 m/s) and for the lower layers (< 10 m) the upper border (0,05 m/s). Using equation (1) airflow for the active ventilation is calculated, so for the cell of a chosen diameter of 12m and the height of the layer of 20m, the apparent air speed of 0,025 m/s was recommended. The calculated optimal airflow for airing the grain is 10.173,6 m^3/h. In table 7 we can find the values for air flow in cells of a diameter from 8m to 20m and an apparent air speed of 0,025 m/s.

$$Q = \frac{d^2 \cdot \pi}{4} \cdot v \cdot 3600 = \frac{12^2 \cdot 3{,}14}{4} \cdot 0{,}025 \cdot 3600 = 10.173{,}6\, m^3/h$$

Q - flow ventilator (m^3/h), d – cell diameter (m), v – apparent airspeed (m/s).

In order to choose a fan, besides the airflow it is necessary to determine the stress of the fan – the pressure drop. The total pressure drop Δp_{tot} (Pa) in active ventilation systems depends on the following: the chosen apparent airspeed, the height of the grain level (h), the type of grain that is stored, the humidity of the grain, bulk density, the presence of impurities in the intergranular space, the resistance in the intake and pressure pipe systems, the resistance in the channel for air distribution in the silo cell or in the floor storage, resistance in the exhaust vents out of the silo cell or floor storage into the atmosphere. The resistance of the grain is an empirical value that can be found in literature sources for every type of grain separately, depending on the traits of the grain in bulk, and the apparent airspeed. The airflow resistance of the grain is shown as a unit pressure drop and is measured in Pascal per meter of the height of the grain layer (Pa/m). Table 8 shows the source data of the unit pressure drop for four types of grain and their humidity under different apparent airspeeds.

Table 8. Unit pressure drop for air temperature of 20ºC while airing through a layer of grain depending on the apparent airspeed.

Type of grain	Grain humidity (%)	Apparent airspeed (m/s)	Unit pressure drop (Pa/m)
Wheat	13	0,025	180
		0,05	260
Maize	14	0,025	80
		0,05	120
Soybean	12	0,025	65
		0,05	105
Sunflower	7	0,025	100
		0,05	130

The example of maize grain will be used to determine the total pressure drop (Δp_{tot}) for airing in a silo cell that has a diameter of 12m, a height of the layer of 20m, and an apparent speed of 0,025 m/s. Individual stress on the intake pipe (Δp_{usis}), pressure pipe (Δp_{potis}), entry of air into the cell through ducts, and the perforated floor ($\Delta p_{perforirani\ pod}$), exit of air from the silo cell into the atmosphere ($\Delta p_{izlaz\ iz\ ćelije}$) vary from case to case. For this example, the collective (Δp_{zbirno}) will be taken with an estimated value of 400 Pa. Based on equations (2) and (3), the total stress of the fan can be calculated. Based on the calculated stress and flow the needed power on the fan shaft can be determined (equation 4) for the degree of usefulness of the fan 0.8. The active power of the electromotor is calculated using the equation (5). Table 9 represents the calculated airflow and the active power of the electromotors for cells of a different diameter, the height of the layer of maize grain H = 20m, and an apparent airspeed of 0.025 m/s.

$$\Delta p_{grain\ high} = \frac{\Delta p}{H} \cdot H = 80 \cdot 20 = 1600\ Pa \qquad (2)$$

$$\Delta p_{tot} = \Delta p_{grain\ high} + \left(\Delta p_{in} + \Delta p_{out} + \Delta p_{floor} + \Delta p_{cell\ out}\right) = \Delta p_{grain\ high} + \Delta p_{total} \qquad (3)$$

$$\Delta p_{tot} = 1.600 + 400 = 2000\ Pa$$

$$P_{fan\ power} = \frac{Q \cdot \Delta p_{tot}}{\eta_{e.m.} \cdot 3600} = \frac{10.173 \cdot 2000}{0{,}8 \cdot 3600} = 7065\ W = 7{,}065\ kW \quad (4)$$

$$P_{active\ power} = \frac{P_{fan\ shaft}}{\eta_{e.m.} \cdot cos\varphi} = \frac{7{,}065}{0{,}95 \cdot 0{,}85} = 9296\ W = 9{,}3\ kW \quad (5)$$

Table 9. Airflow for active ventilation and the active power of the electromotor for silo cells of a different diameter, the height of the maize grain layer of 20m, and an apparent airspeed of 0.025 m/s

Diameter of the silo cell (m)	Airflow for active ventilation (m^3/h)	Fan stress (Pa)	Power on the shaft of the fan (W)	Active power of the electromotor for cell (kW)
8	4521.6	2000	3140	4,13
12	10173.6	2000	7065	9,30
14	13847.4	2000	9616.25	12,65
16	18086.4	2000	12560	16,53
18	22890.6	2000	15896.25	20,92
20	28260	2000	19625	25,82

While projecting a system for active ventilation it is calculated that wheat is the most unfavorable type of grain based on the unit air pressure drop through a layer of grain. Due to the change in resistance, while storing different types of grain in the same silo cell, it is useful for the electromotor to have a frequency regulator that would control the flow of air close to the projected values.

THE SPEED OF COOLING THE GRAIN BY ACTIVE VENTILATION

The economic justification for the use of active ventilation depends on the speed of cooling the grain. The following factors affect the speed of cooling: the type of grain, the humidity of the grain, the temperature of the grain, impurities, the apparent airspeed, and the temperature and humidity of the ambient air. Grains with a higher content of moisture contain a higher specific heat (kJ/kgK), therefore, the cooling speed is slower when compared to the grains with a lower value. Ambient air with a low temperature and a low value of absolute humidity has the greatest potential for cooling. The air temperatures where the difference in the temperature between the air and the grain $\Delta t \geq 10$ºC are the most suitable for cooling grain. With such a temperature difference, the temperature gradient secures an appropriate cooling speed. Of course, the system can, in certain intervention situations, be turned on when the difference is smaller. The cooling time depends on various crucial factors and changes with different states of air. For example, for the grain of maize with a mass of 1684,26 t stored in a silo cell of a diameter of 12m and the height of the layer of 20m, ≈140 h is needed to cool it to a temperature of 20ºC with an apparent airspeed of 0.025m/s and the temperatures of the ambient air of 15ºC and a relative air humidity of 50%. Based on the cooling-working of the electromotor the used electric energy can be calculated, 140h x 9,30 1.301,44 kWh. If the price of industrial electricity is 142 euros/MWh, the total price will amount to 184.80 euros, and the specific costs are 0.109eur/kg of maize.

THE DISTRIBUTION OF AIR IN THE SILO CELLS AND FLOOR STORAGE

The distribution of ambient air into the floor storage is performed through flat perforated floors that are installed during the construction of the warehouse (stationary). With floor storage that doesn't have an installation for the distribution of air, perforated pipes in the shape of a half-cylinder are attached to the floor at certain distances from one another and can be replaced or removed if needed. Silo cells with a flat bottom have perforated openings in the floor made of the so-called cut perforated metal sheets, while for cells with a cone, a variation needs to be made where a roof is installed (similar to a drying facility) to the height of the connection between the cell mantle into the cone. Another possibility when using cells with a cone is the installation of a double cone. Special attention should be paid to the diameter of the opening on the wall of the cell/storage through which cooled air is introduced to the cell. The opening should be as large as possible, not smaller than the diameter of the pressure pipe. In case the opening is smaller, local resistance is created which can lower the flow of the cooling air and by doing that slow down the cooling process in the grain and jeopardize the efficiency of the system. The pressure pipe system from the fan to the connection opening on the silo/storage should be as short as possible. The intake part of the pipe system should be as short as possible and have a filter that would stop the insects from passing through. Quite often the intake part of the pipe system is not needed and just a filter at the fan inlet is enough.

Silo cells of a higher diameter and a lower height of the grain layer are more economical for the installation of the active ventilation system. When the diameter of the silo cell is higher, a greater airflow is possible per ton of stored grain, compared to the silo cells of a lesser diameter. Grain with a higher porosity level creates a smaller amount of resistance to the flow of air through the layer. It is vital to clean the grain beforehand, so the equal porosity of the grain can guarantee an even distribution of air, as seen in the horizontal cross-section, and with that a more balanced and quicker cooling of the grain.

An increased number of impurities and unwanted material in the grain can cause the creation of "pockets" that block the passage of air, and those parts will cool slower. The formation of the cone on the top of the layer of grain creates an increased resistance to the airflow through the middle of the cell. In cells where there is a grain distributor on the filling opening, the positioning of the air currents in the grain layer is more suitable because it stops the cone from forming at the top.

During the active ventilation of the grain, it is especially important to pay attention to the possibility of the appearance of condensation of water vapor that will cause the grain to become wetter. The condensation of water vapors can appear in the following cases:

-condensation of water vapor on the ceiling and the walls of the silo cell or floor storage that are above the layer of grain

-condensation of water vapor in the layer of grain that is in the storage

-condensation of water vapor in the grain in the transportation vehicles.

Condensation of water vapor on the ceiling and the walls of the silo cell, which are above the layer of grain, is created when those surfaces are of a lower temperature than the air temperature coming from the grain layer. When humid air comes into contact with those surfaces, the air temperature is lowered and some of the moisture from the air transfers into a liquid state. Condensed water then drips from the ceiling, or drips from the vertical walls onto the upper layers of the grain causing them to become wet. This occurrence is typical for the periods when the temperatures of the surrounding air are lower, in late autumn or winter months, as well as in the colder nights in the summer months. The intensity of the water condensation depends on how saturated the air coming from the grain, is with moisture and the difference in temperature between the air and the cold surfaces of the storage. The reduction of this issue can be done in the following ways: thermal isolation of the critical surfaces in the storage or the silo cell, a higher number of vents for releasing air from the cell, installation of an auxiliary axial fan (greater airflow, less stress) with a task to speed up the air exiting the storage and to eliminate the air pockets in the corners of the cell-storage; pouring in the grain all the way up to the roof of the silo cell.

Condensation of the water vapors in the layer of grain in the storage happens when the temperature of the grain is of lower temperature than the temperature of the air that flows through the layer. In this case, water vapor from the air of a higher temperature transfers to the grain of a lower temperature and increases its moisture.

The use of the active ventilation of grain should be carefully planned. In centers for drying and storing that are involved in the grain trade keep the grain in storage for a short period of time and the system is useful as a preventive measure used to cool the layer of grain which is susceptible to self-heating (certain silo cells). When storing summer granular cultures, small grains, whose moisture during harvest is equal to the equilibrium special attention should be paid not to lower the moisture of the grain (0,3% - 0,5% za $\Delta t = 10^{o}C$). The mentioned lowering of moisture is not as important for companies that will use their own silos to process the stored small grains. However, the trade-oriented centers for drying and storing need to take into account the JUS standard. Special attention needs to be paid to the autumn grain crops whose moisture when harvesting is higher than the equilibrium, predominantly maize. Trade-oriented centers for drying and storing should dry the grain of maize to a slightly higher moisture value than the equilibrium because the moisture content will be lowered during the active ventilation (0,5% - 0,8% za $\Delta t = 10^{o}C$) and then reach the equilibrium values suitable for trade.

JUSTIFICATION FOR ACTIVE VENTILATION OF GRAIN

The basic justification for the active ventilation systems is the lesser intensity of grain respiration of the stored grain. With a stored grain of a low temperature, aerobic and anaerobic grain respiration is brought down to the minimum, together with the decomposition of the dry matter. We must take into account that the dry matter loss due to grain respiration can reach from 0.3% to 0.5% of the stored mass, and in extreme cases with an increased breakage of the grain of 30%, it can reach a value of 1%. Elevation of the grain, in this way, as the most common way of cooling grain is avoided. By grain elevation we use electrical energy, there is wear and tear on the transport vehicles, and there is an increase in breakage of the grain, which can reach from 0.5% to 1% of the elevated mass in 2-3 elevations. In the example of the silo cell diameter of 12m and the height of the grain of 20m with 1,684,29 tons stored, a lesser intensity of grain respiration of 0.2% which would otherwise lower the value of the stored grain for 486 euros (the price of maize of 0.14 euros or 17.0 dinars per kilogram without tax), can bring a saving of 302 euros, for the same mass 184.8 euros were used for the price of electrical energy needed for active ventilation. If we add into the calculations the expense of elevation of heated grain and the increase of breakage the savings increase even more. With a well-organized and automated system for active ventilation, the need for an empty cell in the silo used for the elevation is avoided. With a grain of a higher value, the savings are greater. Grain moisture when leaving the drier can be somewhat higher than the equilibrium because it will be reduced in the process of cooling. In this way, money is saved during the drying and there is a decrease in expenses needed for the fuel and electrical energy thus also increasing the hourly output of the dryer. With aired grain in a silo cell, the occurrence of self-heating of the vertical layers next to the walls of the cell due to the condensation of moisture in cold nights in the summer months and cold days throughout the year is avoided.

When we compare the system for active ventilation to the granifrigor device, the benefits of active ventilation are as follows: a lesser investment, lesser use of electrical energy, cheaper maintenance, smaller changes in the mass of the grain due to desorption (usually high in granifrigor devices). The downsides of the active ventilation system are as follows: the dependence on the state of ambient air (temperature and relative humidity), compulsory fumigation of the stored grain and the necessity of an automated system that is effective, and a smaller speed of cooling when compared to the granifrigor device.

CONCLUSION

Active ventilation of the grain in storage and silo cells has a positive effect on maintaining the quality of the stored product. Active ventilation can not work for 24 hours, it turns on when the conditions of temperature and relative humidity of the ambient air are reached. Silo cells of a greater diameter and lower levels of grain mounds are more suitable for the installation of the system of active ventilation than cells of a smaller diameter and a higher level of the grain mound. When discussing the speed of cooling, the least suitable culture is maize, followed by wheat, soybean, and sunflower seed. When discussing the unit pressure drop, the least suitable is wheat, followed by sunflower seed, soybean, and maize. It should be remembered that the system for active ventilation is not a negligible electrical power consumer. Its purchase and rational use should be planned carefully. It is necessary to balance the expenses of use and the savings it brings precisely. Installing the automatic controller for turning the system on and off gives the best results without the fear of wetting or drying the grain in the storage. Only with good organization and correct and timely use, the positive effects can be visible. Every center for drying and storing should perform a case study into the financial benefits of purchasing and using an active ventilation system. This study should be based on the policy of the company (trade, processing), technological equipment, and human resources (engineers). An important part of the study will be the recorded data and the experiences of the workers and employees from the past year; loss and breakage of grain, expenses of elevation, percentage of grain broken or with an increased moisture during delivery, expenses of drying, etc. In warehouses where grain is kept for longer periods, there is a greater chance for a successful case study. Centers for storing where the demand for quality assurance of the grain is especially important, such as oil mills, granaries, and milling plants also belong in the group of those who would benefit from performing such a case study.

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