INFLUENCE OF OUTER ENERGY ON RYE GRAIN TEMPERATURE DISTRIBUTION IN MODEL SILO

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INTRODUCTION

Storage time depends on water content in grain and the temperature [15]. Respiration processes occur during storage. Oxygen respiration leads to the emission of great amounts of heat and water. If these products are not quickly carried away, secondary grain moisturizing occurs, which causes further increase of respiration intensity. Self-heating of bulk grain is a result of grain and micro-organism respiration. It can be of focal character. Low thermal conduction of bulk grain is a physical basis of self-heating phenomenon. Processes of temperature and water content increase take place at the same time. Arising differences between temperature and water content invoke their diffusion.

Seasonal and daily temperature oscillations are a serious reason for water migration and changes of its distribution inside the stored material. A precise prediction of water content and temperature of stored grain is necessary for the control of ventilation process [5]. Free water migration depends on several factors: type and quality of the stored grain, grain size and shape, temperature, initial water content, weather conditions, storage duration, sorption and diffusion properties. These factors make the water migration process unstable [1, 2, 3, 6, 7].

Khankari *et al.* [8, 9] found that water migration increased along with the grain temperature increase. Their studies revealed that water migration occurs at all silo dimensions, and it begins earlier in smaller silos.

Grochowicz *et al.* [4] and Kusińska [10, 11, 13, 14] performing the simulation tests using cereal grain observed a very high correlation between results of water content and temperature measurement and their strong influence on the values of horizontal pressure which, in turn, is of great practical importance in silo designing. Measurements of temperature, that is directly associated with water content in grain, are usually made during grain storage. Knowledge on the grain temperature distribution in a silo is necessary for an evaluation of the stored material quality and grain thermal pressure.

The aim of the present study was to evaluate the influence of outer energy on rye grain temperature during its storage.

MATERIAL AND METHODS

Purchased rye grain was characterized with diverse water content in particular unit packages. Water content ranged from 0.113 to 0.136 kg/kg d.m. Before the experiment began, 250 kg of grain was poured out on a sheet made from canvas paulin, thoroughly mixed using shovel then it was poured into plastic barrels with hermetic cover and stored for a day. After that, the grain was poured out again and twenty samples were taken randomly for water content determination. Necessary water weight that should be added to the grain in order to achieve required water content was calculated on the basis of water balance after the mean water content determination. Water amount was calculated using the following formula:

$$W = M \frac{u_o - u_z}{1 + u_o} \tag{1}$$

where:

W – volume of added water intu the grain, kg,

M – mass of watering grain, kg,

 u_0 – required water content in grain, kg/kg d.b.,

 u_z – water content in purchased grain, kg/kg d.b.

Grain was moisturized using distilled water by means of spraying, then mixed and poured into barrels that were hermetically sealed with covers. Barrels were half filled to facilitate the grain's mixing during turning. Grain was mixed every 6-12 hours. It was stored at 15°C for two days. Then, rye was poured out onto the sheet, shoveled, mixed partially in a drum mixer, shoveled again and checked for water content. The principle to maintain 15°C of grain was kept during all these procedures. Therefore, grain was moisturized till achieving the material with the required water content. Experimental material prepared in the above way was applied for stand measurements.

Measurement stands of own design for measurements of cereal temperature with a possibility to maintain outer temperature at the constant level during grain storage were applied during tests. Thermal energy was supplied using constanttemperature water, which simulated the effect of surrounding air temperature or solar radiation increase.

The scheme of measurement stand is presented in Fig. 1. Its general element is a silo consisting of cylindrical part (1) of 600 mm inner diameter and 1200 mm height, conical part with bolt and cover with isolation material (foamed polysty-rene) lining. Cylindrical and conical parts is equipped with thermostatic jacket, to

which water of constant temperature is delivered from ultrathermostat (4) of UH-16 type. In the cylindrical part, along the generatrix, there are holes of 38 mm diameter each at the following distances from the cylinder edge: 175, 275, 375, 475, 575, 675, 775 and 875 mm. The holes were for temperature measurements at five distances from reservoir's symmetry axe (0, 75, 150, 225 and 300 mm). The scheme of measurement points distribution is presented in Fig. 2. Fe-CuNi thermoelements (2) of I-TP 11 type, the signal from which was transmitted to digital measuring instruments (3) of AR 592 type, were applied for temperature measurement. Temperature values were read with 0.1°C accuracy. Reservoir and elements being in contact with the grain were made of stainless acid resistant steel.



Fig. 1. Schematic diagram of the test station: 1 – silo, 2 – thermocouples, 3 – temperature gauges, 4 – thermostat

Fig. 2. Arrangement of measurement points in the silo

Before the study began, silo cleanness, efficiency of controlling and measuring device should have been checked and proper water temperature in thermostatic jacket should have been adjusted. Then the silo was filled with thr prepared material up to 1050 mm height, hermetically shut with the cover and an experiment lasting 21 days began. Grain temperature measurements were made in forty points of the silo at the same time everyday.

Stand tests were carried out for 'Wibro' rye with three initial water contents, u_0 : 0.136, 0.190 and 0.250 kg/kg d.m. Water temperature, t_o , in thermostatic jacket was maintained at the constant level: 15, 20 and 25°C. Measurements were made in three replications.

RESULTS

The increase of grain temperature was observed during rye grain storage under planned conditions. Mean temperature values in the reservoir depending on the initial water content, storage time and outer temperature are presented in Fig. 3.

During the storage of rye with $u_0 = 0.136$ kg/kg d.m. at a constant outer temperature (15°C) (Fig. 3a), slight changes of mean grain temperature inside the silo

were recorded. Mean temperature did not change for the first four days, but starting from the fifth one it began to gradually increase to 16.76°C at the last day. At outer temperature 20° and 25°C, the mean grain temperature started to grow just at the second day of storage achieving 20.61° and 25.53°C, respectively. During grain storage of $u_0 = 0.190$ and $u_0 = 0.250$ kg/kg d.m. (Fig. 3b and 3c) under extremal conditions ($t_o = 25^{\circ}$ C), high mean values of temperature inside the reservoir were recorded (35.5° and 43.3°C). Higher values of initial water content and outer temperature caused more significant increase of rye grain temperatures. a)



Fig. 3. Mean rye grain temperature in the silo depending on storage time and outer temperature for initial water contents: a) $u_0 = 0.136 \text{ kg/kg d.m.}$, b) $u_0 = 0.190 \text{ kg/kg d.m.}$, c) $u_0 = 0.250 \text{ kg/kg d.m.}$

b)

c)

In all cases, temperature did not distribute uniformly in longitudinal sections of the silo. From Fig. 4a it follows that after 21-day rye grain storage at outer temperature 15°C, grain temperature increased up to 18.5°C only at points on 475-875 mm levels and those distant to 50 mm away from the axe. Then it dropped to 16°C in radial and axial directions. Temperature distribution in grain of $u_0 = 0.136$ kg/kg d.m. after 21-day storage at outer temperature 25°C is presented on Fig. 4b. In this case, the lowest temperature values occurred at the silo's axe (23°C) and the temperature increased in horizontal direction up to 27-28°C near the reservoir's walls. Temperature increase was quite uniform along the silo's height.

Much higher temperature increase occurred during rye storage of initial water content to 0.190 kg/kg d.m. It is presented in Fig. 5. After 21-day storage of material at outer temperature 15° C (Fig. 5a), the highest grain temperature was observed at points localized on silo's axe at the level of 775 mm (35.5°C). Temperature decreased to 33-34°C along with the distance from the axe, and even to 27°C at the bottom. Increase of outer temperature to 25°C (Fig. 5b) caused the increase of temperature (up to 40°C) near the wall at the level of 675-775 mm. Lower temperatures were recorded on the reservoir's axe at the same level (36-37.5°C), and 30°C at the bottom.



Fig. 4. Temperature distribution in rye grain of initial water content $u_0 = 0.136$ kg/kg d.m. on 21^{st} day of storage at outer temperatures: a) 15° C, b) 25° C



Fig. 5. Temperature distribution in rye grain of initial water content $u_0 = 0.190 \text{ kg/kg d.m. on } 21^{\text{st}} \text{ day}$ of storage at outer temperatures: a) 15°C, b) 25°C



Fig. 6. Temperature distribution in rye grain of initial water content $u_0 = 0.250 \text{ kg/kg d.m. on } 21^{\text{st}} \text{ day}$ of storage at outer temperatures: a) 15°C, b) 25°C

Fig. 6a and 6b illustrate temperatures of rye of initial water content 0.250 kg/kg d.m. and stored at outer temperatures 15° and 25°C. Temperature changes in these cases were the highest. At 15°C, the difference between temperature on the axe at 675-775 mm level was 8°C (t = 42°C on axe, t = 34°C near the wall). At 25°C of outer temperature, rye grain achieved 46.5° near the reservoir's walls. In all cases stored at 15°C regardless the initial water content, the temperature was the highest at points localized on silo's axe at the level h = 675-775 mm. Higher values corresponded to higher initial water contents. Moreover, during grain storage at 25°C, natural respiration processes were intensified by the delivery of outer energy. Temperature increased in all points in the silo (also on axe). Applying grain of only $u_0 = 0.136$ kg/kg d.m., uniform temperature increase along the height in the direction from the axe to the wall was found. For the grain of $u_0 = 0.190$ kg/kg d.m. the fastest temperature rise was observed in the upper parts and was still the highest near the silo's wall. For the grain of $u_0 = 0.250$ kg/kg d.m., the maximum temperature values were achieved at all points of the reservoir. Temperature at the level h = 575-675 mm was the same as on the whole horizontal section amounting to 45.5°C. Its range spread in horizontal direction towards the wall. Temperature increase was closely associated with rye respiration processes and the increase of water content (up to 0.030 kg/kg d.m.). Increase of temperature proves the oxygen respiration process. Also physical properties change during rye storage [12].

Grain temperature measurement results were subjected to variance analysis showing that the initial water content u_0 , outer temperature t_o , storage time τ , measurement level h and distance of the point from silo's axe r, had a significant influence ($\alpha < 0.01$) on these values. Detailed variance analysis performed using Tukey's method proved that in the majority of cases, mean temperature values for chosen levels of an independent variable also significantly differed from one another. Storage time exerted the greatest effects on rye temperature value, which was illustrated by correlation coefficient (r = 0.656) and initial water content (r = 0.581). The increase of the distance from the axe caused a slight decrease of mean rye temperature, which was confirmed by the negative value of correlation coefficient (r = -0.023). The achieved study results have an absolute error 0.1°C and relative error ranging in 0.219-0.66%. Mean values, standard deviations and standard error of temperature value are presented in Fig. 7.

Applying multiple regression analysis, influence of initial water content u_0 , outer temperature t_o , storage time τ , measurement level h and distance of the point from silo's axe r on grain temperature t at any point within the reservoir was described. The resulting formula is the following:

$$t = -6,784 + 90,52u_0 + 0,241t_0 + 0,872\tau + 0,0018h - 0,0016r$$
(9)



Fig. 7. Standard deviations, standard error and mean values of temperature value

It is the first-order polynomial (standard estimation error 3.33). Comparing the achieved results with those from similar study using wheat grain [14], it can be stated that rye grain showed weaker ability to self-heating, which was associated with its physical properties and chemical composition.

CONCLUSIONS

The following conclusions could be drawn from the analysis of the result referring to temperature distribution in rye grain stored at constant outer temperature:

1. Rye grain temperature in the silo significantly depends on the initial water content, outer temperature, storage time and localization of measurement point.

2. For grain of the initial water content $u_0 = 0.136$ kg/kg d.m. changes of studied parameters were slight, but statistically significant. Higher initial water content caused higher increase of grain temperature.

3. Value of grain temperature during storage at 15°C increased at first inside the reservoir, and then it was spread in horizontal and vertical directions.

3. In all cases, an increase of outer temperature caused an increase of temperature near the walls at the first day of storage, and then at other points. Grain temperature of higher initial water content increased much faster in the whole silo. The highest grain temperature increase occurred on the levels from 575 mm to 775 mm.

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SUMMARY

Results of simulative study on rye grain temperature distribution in silo's longitudinal section were presented in the paper. 'Wibro' rye with initial water contents of 0.136, 0.190 and 0.250 kg/kg d.m. and stored at 15°, 20° and 25° of outer temperature for 21 days under oxygen respiration conditions was applied for tests. Grain temperature was recorded everyday at 40 measurement points. Study results were subjected to regression analysis and the formula combining the grain's temperature depending on initial water content, outer temperature, process duration and measurement point location was derived. Variance analysis revealed that all the experimental variables exerted a significant effect on rye grain temperature.