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MASS EXCHANGE IN ADJACENT LAYERS OF GRAIN MATERIAL STORED IN SILO*

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A b s t r a c t. The paper presents the results of a study on the process of moisture diffusion during barley grain storage in a grain storage silo. The moisture migration was caused by concentration gradient. The study was conducted using a model test station and consisted in the measurement of barley grain moisture and temperature in a silo, and in measuring the pressure exerted by the grain bulk on the silo wall.

Analysis of the results showed that none of the parameters studied was stable. It was found that when the grain moisture content applied was 16% in the bottom layer and 10% in the upper layer the average value of grain moisture content in the silo increased from 13.2% to 14.1% over the ten days of the process, while with reverse positioning of the layers in the silo the corresponding increase reached 13.8%. This was due to additional precipitation of water in the course of the process of grain respiration. Moisture diffusion caused an increase in the temperature of the grain within the silo (up to 33°C at ambient temperature of 16°C). Another important effect of the moisture diffusion was the swelling of grains, which caused an increase in the pressure of the barley grain bulk against the silo wall. The highest increase in the wall load was observed at the boundary line between layers of grain of different moisture content levels. The changes in the values of the parameters under study were described by means of regression equations.

K e y w o r d s: moisture, diffusion, grain, storage, wall load

INTRODUCTION

Cereal grain is characterised by absorptive and hygroscopic properties due to its capillary and porous structure. It is a living organism in which vital processes take place, such as respiration and post-harvest maturation. Carbon dioxide, water and a large amount of thermal energy produced as a result of oxygen respiration bring about an increase in the grain temperature and moisture content, as well as growth of microorganisms, bacteria and mould causing mow-burn of the grain.

Mass exchange in agricultural raw materials and products is one of the most important phenomena in the food industry. The existing theories of mass exchange are applicable to porous and capillary materials such as clay, sand or silica. However, they cannot be used for the description of plant materials because of their complex structure and considerable diversity.

The interesting and involved processes taking place in grain bulk during storage encouraged the authors to study the phenomenon of mass exchange between two grain layers of different moisture content levels placed in a storage silo, as well as related processes. The study was carried out for the grain of the Klimek barley variety.

MOISTURE DIFFUSION IN PLANT MATERIALS

The process of mass exchange is based on the phenomenon of substance transfer from one phase to another. Hygroscopic bodies, such as cereals, absorb water until they reach equilibrium. The equilibrium moisture content is

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one of the factors which determine the level of moisture content in a material, its rate of drying or wetting. The driving force of the process of diffusion is the difference between the chemical potentials of the component. The chemical potential of the component (being a function of pressure, temperature and concentration) is not always possible to calculate. The basis for the mathematical analysis of the component diffusion is Fick's law, dating back to 1855, as quoted, among others, by Crank [3]. Fick's equation was used by Pixton and Griffiths [9] to describe moisture diffusion through grain bulk of high moisture content. The relation they arrived at can be used when we know the initial vapour pressure or the obstructive coefficient during water vapour diffusion in grain bulk. Pixton and Griffiths' studies were continued by Thorpe [11]. He analysed isothermic diffusion of moisture in wheat grain (γ = 0.53). He described the process by means of a mathematical equation.

A large number of solutions of Fick's diffusion equation were presented by Crank [3]. However, they did not provide simplified forms of such solutions. The method of Crank and Nicolson was chosen by Benedetti *et al.* [1] for modelling the process of moisture migration during maize grain storage. He used a test station, the principal element of which was a tube filled with maize grain of uniform moisture (14-15%). The driving force of the process was temperature gradient. The lower part of the tube was heated to a temperature of 40-41°C, while the upper part was cooled down to 4-5°C. Moisture diffusion was very slow under such conditions. The diffusion and the accompanying processes resulted in an increase in the mean value of maize grain moisture content by 0.24%. In the lower part of the tube the moisture decreased by 5.45%, while in the upper part it increased by 2.61%. Benedetti obtained a high level of agreement between the experimental data and the values calculated by means of the mathematical model.

A theoretical study on continuous drying of grain material were conducted by Medeljkov [8]. He developed a mathematical model describing the phenomenon of heat and moisture exchange in a dense layer of grain material in the process of convection drying. He utilised the concept of the quasi-uniform medium and of elementary layers. He presented a model which described special cases as well as phenomena occurring in the course of drying with unheated air and with active ventilation.

Gough *et al.* [5] studied physical changes in brown rice stored in metal cereal grain silos. The study was conducted in the climatic conditions of South Korea and consisted in comparing changes in rice grain temperature and moisture content when stored in silos with and without thermally insulated walls, as well as in silos with grain ventilation. The period of storage was 8 months. Gough found that water precipitated on silo ceilings irrespective of whether the silo walls were thermally insulated or not. In silos with thermal insulation grain moisture content at the silo ceiling increased from 13-14% to 16-20% between the 220th and the 240th days of storage. The increase in grain moisture content was caused by air convection brought about by the process of respiration of insects or by spontaneous air movement within the silo, and possibly also by the diffusion of water vapour from inside the rice grain mass upwards. The rice grain moisture content was the highest on the north side of the silo. The difference in rice grain moisture content between the silos with and without thermally insulated walls was 1%.

Brusewitz [2] studied the variability of grain moisture during drying, mixing and storage. His study was conducted on individual kernels. On the basis of the results of his study he found that moisture distribution in grain dried artificially was not a normal but a multimodal distribution. He obtained much narrower distributions of grain moisture content in microwave drying than in heated air drying. He showed that mixing two grain samples of different moisture content levels together will not bring about equalization of the moisture content of individual kernels even 24 hours after the mixing.

Watts *et al.* [12] conducted the process of simulation of absorption drying of maize, wheat, barley and oats using sodium bentonite. They developed a mathematical model for the calculation of curves of simultaneous drying of grain and wetting of loam. They performed analyses for three stages of the process of grain drying: moisture migra tion from the grain to the surrounding air, moisture adsorption from the air by loam, and equalisation of relative humidity to the moisture content of the loam. They obtained good agreement between experimental data and values calculated by means of their mathematical model when a low ratio of grain to loam was applied. The ratio was calculated on the basis of moisture balance obtained from the experimental data.

Changes in a mixture of dry and wet barley grain were studied by Henderson [6]. She proposed formulae for the determination of the resultant moisture content of the grain mixture with relation to the temperature and the composition of the mixture. She showed that the time of equalisation of moisture was very short in a mixture composed of one third of dry grain of a moisture content of 7% and two thirds of wet grain of a moisture of 23%. Over 90% of the changes occurred within three days, and total equalization of the grain moisture took place after 20 days. She observed the appearance of hysteresis of about 1% within 28 days, and faster equalisation of moisture at higher temperatures.

Haman *et al.* [4] report that most authors dealing with the subject used Thomson's formula for the determination of hysteresis.

Syarief *et al.* [10] conducted studies aimed at the development of methods for the determination of moisture diffusion in maize grain. They developed a new method basing on the thermo-gravitation analysis of component parts of maize kernels. The method is based on a combination of experimental data on the rate of sorption and desorption with numerical modelling of the two diffusion processes. They found that the coefficient of diffusion increased in a linear manner with increasing moisture and was the highest for the germ, almost four times lower for the endosperm, and five times lower for the involucre.

Kusińska [7] gave the results of measurements of changes in the moisture, temperature and silo wall load during silo storage of wheat grain at various moisture concentrations in grain layers. She described the process by means of mathematical equations.

METHOD

The study was carried out using the laboratory stand presented in Fig. 1. The main component of the stand was a silo of 1200 mm in height at its cylindrical part and 600 mm in diameter. The instrumentation of the stand made it possible to measure the temperature and the moisture content values at 40 points arranged at the levels of 175, 275, 375, 475, 575, 675, 775 and 875 mm and at different distances from the silo axis, the distances being 0, 75, 150, 225 and 330 mm. Grain samples for moisture content determination were taken by means of a special sampler which made it possible to sample the grain from required points. The grain material was sampled by lowering the sampler down the holes which were used to take temperature measurements by means of thermocouples 2. Temperature values were read out from a digital temperature gauge 3. The values of the grain were additionally measured by means of strain gauges 4 which were connected to a silo wall load indicator 5. The top the silo was tightly closed with a cover lined with insulation material. The silo jacket was kept at a constant

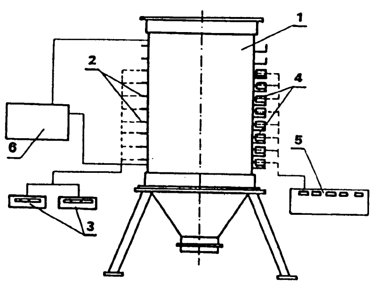


Fig. 1. Schematic diagram of the test station 1 - silo, 2 - thermocouples, 3 - temperature gauges, 4 - strain gauges, 5 - silo wall load indicator with amplifier, 6 - thermostat.

temperature of 16°C by means of water supplied from a thermostat 6. The arrangement of the measurement points is shown in Fig. 2.

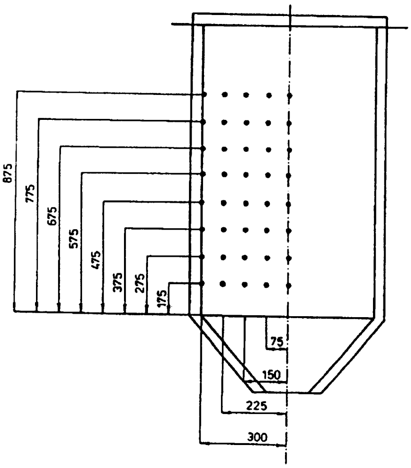


Fig. 2. Arrangement of measurement points in the silo.

The scope of the study included two ten-day cycles. During the measurements two different levels of initial moisture content in the bottom (W_1) and top (W_2) grain layers were used. These were W_1=16% and W_2=10% for the first ten-day cycle and W_1=10% and W_2=16% for the second cycle. The boundary between the grain layers was at the height of 500 mm. In order to obtain the required moisture content, the barley grain was wetted with water and tightly sealed in plastic barrels for three days. Every 8 hours the grain material was stirred thoroughly to obtain uniform moisture distribution. The barrels with the barley grain were kept in a controlled climate chamber at a temperature of 16°C.

RESULTS

The results of moisture measurements during the storage of barley grain of the Klimek variety are presented in Fig. 3. In both cases the difference between the moisture content levels of the two grain layers gradually decreased, but the moisture content did not equalise over the ten days of the cycle. Water migration was faster when barley grain of 16% moisture content was placed in the lower part of the silo. On the 10th day moisture content distribution along the height of the silo was nearly linear in character. In the other case, when barley grain of 10% moisture content was placed in the lower part of the silo, a sharply defined boundary between the two grain layers, in terms of their moisture content, remained throughout the duration of the test cycle.

The processes of respiration of the barley grain produced additional amounts of water, resulting in an increase in the average moisture content of the grain in the silo. In the first case the average moisture content value increased from 13.2% to 14.1%, and in the second case to 13.8%. The higher increase in the average value of grain moisture content corresponded to the higher grain moisture content in the lower part of the silo. The greatest changes in grain moisture content took place at the line of contact between the two layers of grain. Moisture

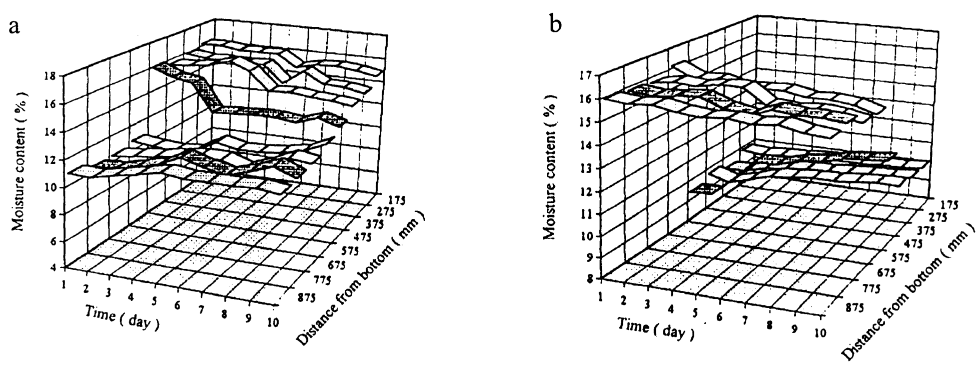


Fig. 3. Results of study of Klimek barley grain moisture content: a) moisture of bottom layer W_1 = 16% and of upper layer W_2 = 10% ; b) moisture of bottom layer W_1 = 10% and of upper layer W_2 = 16%.

content always assumed the highest values at points located along the axis of the silo. The values decreased gradually and slightly towards the silo wall. In the course of the tests water precipitation was observed on the silo cover and on the upper portion of the silo wall, accompanied by processes of moulding and grain germination.

Figure 4 presents the results of temperature measurements. Higher temperature values always corresponded to higher moisture content. Increase in grain moisture content was conducive to spontaneous heating of the grain which was due to intensified processes of grain respiration and to the growth of bacteria and mildew. In the first part of the experiment the temperature of barley grain increased to 33°C (in the lower part of the silo), and in the second part to 26°C (in the upper layer of the grain). Barley grain temperature at points located along the axis of the silo was always higher than closer to the silo wall.

Changes in the barley grain moisture content influenced the values of silo wall load (Fig. 5). Absorption of water and grain swelling resulted in an increase in the wall load. The wall load always increased more in the grain layer which initially had a lower moisture content. The greatest changes in the silo wall load always occurred close to the line of contact between grain layers of different moisture content levels. In the first case, when moisture diffusion was directed upwards, barley grain pressure against the silo wall at the height of 475 mm increased, over the ten days of the test cycle, from 0.55 kPa to 1.04 kPa. On the third day of the cycle the wall load reached a maximum of 1.28 kPa which decreased over the following days. This may have been due to putrefaction processes.

In the second part of the experiment, when swelling took place in the lower layer of grain in the silo (grain with lower initial moisture content), the wall load increase observed at the same height was up to 2.15 kPa. In this case the greater silo load pressure values were due to the additional pressure from the upper layer of grain.

The results of the study were subjected to variance analysis. The analysis showed that the results of measurement of barley grain moisture and temperature in the silo were significantly affected (at the level of 0.01) by the following factors: distance from the silo bottom and from its axis, duration of the process, and the manner of grain layer arrangement. The values of silo wall load, on the other hand, were significantly affected (at the level of 0.01) by the height of the measurement point, the duration of the process, and the arrangement of grain layers in the silo.

The results were also subjected to regression analysis which made it possible to derive equations describing the parameters under study. The regression equations are presented in Table 1.

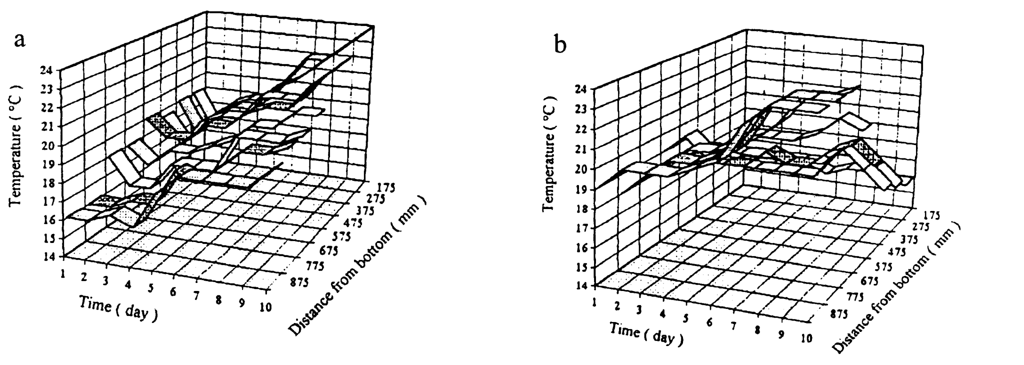
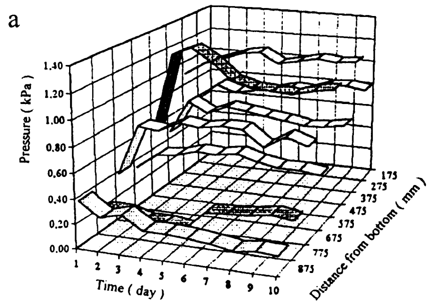


Fig. 4. Results of study of Klimek barley grain temperature: a) moisture of bottom layer W_1 = 16% and of upper layer W_2 = 10% ; b) moisture of bottom layer W_1 = 10% and of upper layer W_2 = 16%.



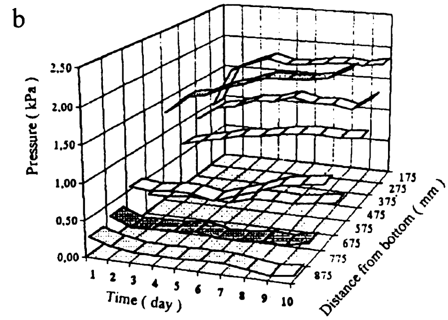


Fig. 5. Results of study Klimek barley grain silo wall load: a) moisture of bottom layer W_1 = 16% and of upper layer W_2 = 10% ; b) moisture of bottom layer W_1 = 10% and of upper layer W_2 = 16%.

T a b l e 1. Regression equations describing moisture, temperature and wall load of Klimek barley

Parameter	W_1/W_2	Equation	Determination coefficient (%)
Moisture content (%)	16/10	$W = 15.6071 + 0.0107h - 0.0047r - 0.0554t$	80.28
	10/16	$W = 17.4373 - 0.0082h - 0.0075r - 0.0372t$	71.75
Temperature (°C)	16/10	$T = 15.5923 - 0.0052h - 0.0080r + 0.1740t$	69.23
	10/16	$T = 18.2394 - 0.0034h - 0.0033r + 0.5052t$	78.68
Wall load (kPa)	16/10	$P = 1.957 - 0.0021h + 0.1432t$	75.08
	10//16	$P = 1.154 - 0.0009h + 0.0728t$	77.09

W_1 - moisture content of bottom layer (%), W_2 - moisture content of upper layer (%), h - height (mm), r - distance from the silo axis (mm), t - time (days).

CONCLUSIONS

1. Barley grain storage in silos in layers of different moisture content is accompanied by significant changes in the values of the moisture content, temperature, and wall load.

2. Moisture diffusion is faster when barley grain of higher moisture content is placed at the lower part of the silo. The diffusion causes an increase in grain temperature and in the silo wall load.

3. Greater values of silo wall load are related to the grain layer with the lower initial moisture content.

REFERENCES

1. **Benedetti B.C., Douglas M.P., Stenning M.P.:** Modelling diffusive moisture migration in stored bulk maize. Agriculturale Eng., Madrid, 96F-055, 1996.
2. **Brusewitz G.M.:** Corn moisture variability during drying, mixing and storage. J. Agric. Eng. Res., 37, 281-288, 1987.
3. **Crank J.:** The Mathematics of Diffusion. Clarendon Press, Oxford, 1975.
4. **Haman J., Szot B., Woźniak W.:** Problems of heat and mass exachange in plant materials. (in Polish). Problemy Agrofizyki, Ossolineum, 9, 1973
5. **Gough M.C., Cheigh H.S., Kim S.K., Kwon T.W.:** Physical changes in stored bulk rice. J. Agric. Eng. Res., 37, 57-71, 1987.
6. **Henderson S.:** Moisture transfer between mixed wet and dry barley grains. J. Agric. Eng. Res., 37, 163-170, 1987.
7. **Kusińska E.:** Mass diffusion between grain layers inside silo (in Polish). Zesz. Probl. Post. Nauk Roln., 425, 109-114, 1996 .
8. **Medeljkov M.J.:** Mathematical modelling of the process of convection drying of grain materials (in Russian). Sov. Pol. Tech., 168, 115-122, 1987.
9. **Pixton S.W., Griffiths H.J.:** Diffusion of moisture through grain., J. Stored Prod. Res., 7(3), 133-152, 1977.
10. **Syarief A.M., Gustafson R.J., Morey R.V.:** Moisture diffusion coefficients for yellow dent corn components. Trans. ASAE, 30(2), 522-528, 1987.
11. **Thorpe G.R.:** Moisture diffusion through bulk grain. J. Stored Prod. Res., 17, 39-40, 1981.
12. **Watts K.C., Bilański W.K., Menzies D.R.:** Simulation of adsorption drying of corn, wheat, barley and oats using sodium bentonite. Can. Agric. Eng., 29(2), 173-178, 1987.