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EFFECTS OF MOISTURE CONTENT OF GRAIN LAYERS AND THEIR ARRANGEMENT IN THE SILO ON THE TEMPERATURE AND PRESSURE DISTRIBUTION

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Abstract. In the present paper, results of temperature and pressure measurement of some cereals (triticale, rye, oat) along with the vertical silo wall were presented. Laminar filling of the silo with layers of various moisture content (8 and 16% w.b.) was applied. Respiration processes and differences in the moisture content caused a significant increase in temperature. During the 10-day study cycle, oat temperature increased up to 45 °C, that of triticale to 39 °C and rye to 25.5 °C. In all the cases, temperatures increased with the increase of storage time. Higher temperatures were obtained when the lower layer had 8% w.b. moisture content and the upper - 16% w.b., but lower temperatures were observed when placement was reversed. The highest temperatures were noted at the border between layers. Temperature of grain situated along the silo symmetry axis was higher than at its walls. The highest load values were obtained for triticale (3.8 kPa), the lowest for oats (1.88 kPa). For all the cases, higher load values occurred at the lowest moisture content of grain in the lower layer. Index of load increment in the lower layer amounted to 3.1 for triticale, 2.25 for rye, and 3.13 for oats.

Keywords: cereals, silo, temperature, pressure distribution

INTRODUCTION

Loads occurring in the silo walls and bottom, that are influenced by inner and outer factors, are very important parameters for bin designers. Factors determining the storage conditions - mainly grain temperature and its moisture content - are, in turn, important during cereal storage. Those parameters are closely connected with one another and they affect grain quality. Seed stored in a bin is never uniform in its moisture content. Cereals are the material of a capillary-porous structure with high susceptibility to water absorption and desorption. Water diffusion in a silo causes seed swelling and increase of loads on the walls and bottoms of the bin. Biological processes are responsible for self-heating of the seeds. The influence of thermal parameters should be taken into account both by designers and technologists.

THERMAL PHENOMENA DURING GRAIN STORAGE IN A BIN

Ambient temperature interaction with cylindrical bins can be the reason for significant wall deformations leading to damage of the bin metal cover in some extreme cases. Silo application, localisation and temperature ranges associated should be taken into account choosing material [3]. Low outer temperature often causes enormous loads in the wall of a bin filled with grain. Loose material load, wind pressure, snow load and loads from any other devices are calculated while designing a bin.

Li *et al.* [9] carried out experiments on the loads in the walls of a bin with 0.9 m diameter and 1.2 m height made from sheet aluminum of 0.8 mm thickness, filled with grain. They applied three measurement cycles for the nominal temperature change in the range of ±10 °C. At the temperature drop, mean load increase was 0.22 kPa/°C for the first case, 0.36 kPa/°C for the second, and 0.38 kPa/°C for the third. The above authors [10] worked out a mathematical model for the calculation of thermal loads based on the finite element model using the equation of elastic-viscoplastic state. They found that theoretically calculated load values were higher than the measured ones by 32, 55 and 78% at the temperature decrease, and by 38, 45 and 52% at the temperature increase.

Khankari *et al.* [6] underlined that theoretically safe moisture content for long-term grain storage becomes dangerous due to migration or redistribution of water inside the bin. They presented model for the calculation of temperature and water changes as well as for the air flow due to the natural convection in the stored bulk grain. They proved that water migration takes place in the silo of any size, but it can be observed earlier in smaller bins.

According to Zhang *et al.* [13], temperature changes very clearly influence load directions and horizontal to vertical loads ratio. They draw this conclusion on the basis of analysis of two bins with different sizes filled with wheat grain with 10% moisture content. They described load distribution invoked by thermal processes using a two-dimensional finite element theory. Zhang *et al.* [12] additionally proved that the phenomenon of seed swelling and appearance of extreme high loads in the bin construction took place during grain moisturizing in the silo. They elaborated a mathematical model for the calculation of the bin construction loads due to this phenomenon. They assumed that the volume increase of a single grain is proportional to the amount of water absorbed. For the silo of 6.15 m height and 4.2 m diameter filled with maize grain, the index of load increase was 8.0-8.6 at the moisture content increase by 10%. Xu *et al.* [11] underlined that the EP 433 standard elaborated by ASAE recommends moisture content range of 1-2% during grain storage in the silo in order to avoid high loads caused by seed swelling.

Jayas [5] studied stimulation of grain temperature during storage in the loose state. He estimated the influence of the following parameters on the temperature: bin diameter, layer height, type of material the silo wall was made from, silo shape and grain mixing with platform auger. He observed time delay between outer and inner temperature changes near bin center. It was the higher, the larger silo diameter. Narrow and tall bins maintained lower temperature than the short with large diameter. In the silos made of zinc coated sheet, higher temperatures occurred than in those painted white. The bin shape did not have any significant influence on the grain temperature. Similarly, grain mixing had no significant affect during longer storage time. It efficiently lowered grain temperature near the silo center by about 10 °C just after the process.

Three-dimensional model of temperature distribution inside the bin for grain storage was elaborated by Alagusundaram [1]. The silo user who operates the model should measure temperature distribution in the beginning of simulation and meteorological data (insolation, wind velocity, air temperature). This model showed, for instance, that temperature is by 5-15 °C higher at the insolated side of the bin than at the shadowed side, which is not shown in the two -dimensional models. Knowledge on the thermal properties of grain, bin wall material, soil and air is necessary for the model application. The a.m. author obtained high consistency between simulation and experimental results using real silos filled with rape-seed and barley.

Water condensation on the walls and roofs of bins is a frequent problem. In order to observe the moment of condensation during white rice storage, Liu *et al.* [8] carried out laboratory studies. Rice at 10 °C initial temperature and 13.5% moisture content was stored for 6 months in a cylindrical bin at 25 °C outer temperature. After grain temperature increased up to 25 °C, they cooled it with water flowing in vinyl pipes. Grain cooling rate was a logarithmic function of the cooling pipes spacing. Condensation took place at the spacing below 2 cm, and above 6 cm, it did not occur. Grochowicz *et al.* [4] also described water condensation on the covers and walls of bins during barley storage. They concluded that due to barley respiration, water desorption occurred. This was the reason for the increase grain mean moisture content from 13.2 to 14.1%. The increase of loads on the walls and an increase of grain temperature followed. The temperature altered from 16 up to 33 °C due to self-heating. The process caused additional loads in the silo wall. Further results of the study on the loads on the cylindrical bin wall were presented by Kusińska [7]. She carried out experimental studies on the influence of moisture gradient between the layers of stored grain and storage time on the distribution of loads on the bin wall. The material was wheat, barley and oats grain. She found that the initial values of pressure and its increase depended on the type of grain (its physical properties), moisture content of layers and storage duration. The highest load of grain was observed for wheat grain. During storage in a closed silo at 15 °C ambient temperature, 16% moisture content of the lower and 7% of the upper grain layer, loads on the wall increased 2.24 times after 10 days. Water diffusion process can also be caused by the temperature gradient. It was examined for maize seeds by Benedetti *et al.* [2]. They stored grain in a pipe with lower part heated up to 40-41 °C, and upper part cooled to 4-5 °C. In such conditions, diffusion was slow. The increase of mean water content by 0.24% occurred due to diffusion and some additional processes.

MATERIAL AND METHODS

Experimental tests of temperature and pressure during triticale, rye and oat storage were carried out. Assumption as to the grain moisture content during filling are not the same for individual particular silos. Two grain layers of different moisture content were applied in the model chamber. At the first stage of study, moisture content of the upper layer was W_u= 16% w.b., and that of the lower, W_l = 8% w.b. At the second stage, moisture content in the layers was reversed. It was planned to estimate the effect of moisture content in the layers and the way of their location on the temperature and pressure distribution. The scope of the study included six ten-day cycles.

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 height of its cylindrical part and 600 mm diameter. Equipment at the stand made it possible to measure temperature 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, i.e. 0, 75, 150, 225 and 300 mm. Temperature values were measured by a termocuple 2 and read out from a digital temperature gauge 3. The values of the grain pressure against the wall of the silo were additionally measured by means of strain gauges 4 which were connected to the 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 temperature of 16°C by means of water supplied from a thermostat 6. The arrangement of the measuring points is shown in Fig. 2.

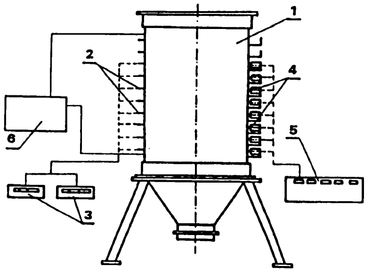


Fig. 1. Schematic diagram of the test station: 1 - silo, 2 - thermocouples, 3 - temperature gauges, 4 - strain gauges, 5 - silo wall load indicator with amplifier, 6 - thermostat.

The silo was filled with grain of given moisture content (W_l) to the height of 525 mm, and after precise surface levelling, it was filled up to 1000 mm with grain with W_u moisture content. In order to obtain the required moisture content, grain was wetted with water and tightly sealed in plastic barrels for three days. Every 8 h the grain material was stirred thoroughly to obtain uniform moisture distribution. The barrels with grain were kept in a controlled climatised chamber at a temperature of 16 °C.

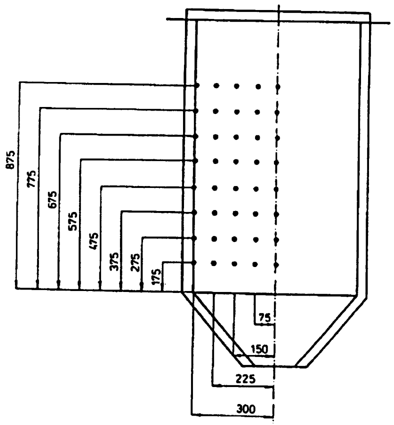


Fig. 2. Arrangement of the measuring points in the silo.

The pressure exerted by the cereal grain on the silo wall, and the grain temperature at particular points within the silo were measured once a day.

RESULTS AND DISCUSSION

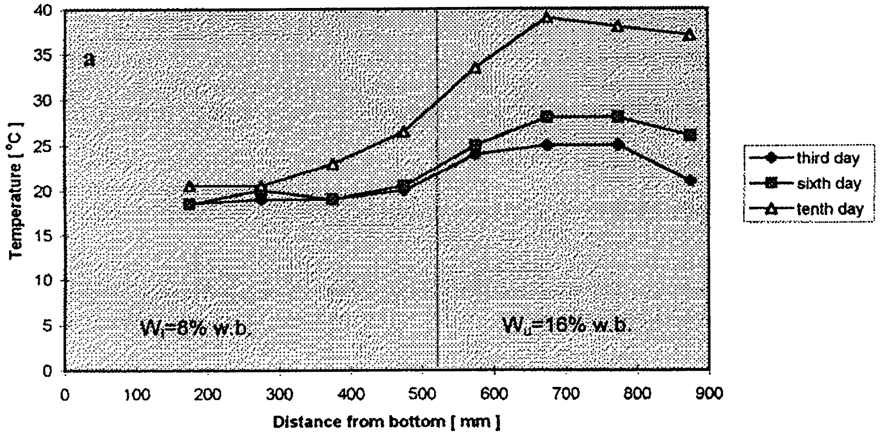
Distribution of triticale grain temperature in the layers at the silo wall is presented in Fig. 3. The plots show data obtained after the 3rd, 6th and 10th day of cereal storage. In the first case (Fig. 3a), when the moisture content of the lower layer was lower (W_l = 8% w.b.) than that of the upper one (W_u = 16% w.b.), very quick temperature increase was observed at the silo wall. The highest values were noted for the upper layer. Higher moisture content caused faster respiration and more intense heat release. In the upper part of the chamber, temperature increased from 16 to 25 °C after three days, to 28 °C after 6 days, and to 39 °C after 10 days. The highest temperature increase occurred at the border layers, i.e. where the difference in the moisture contents was the highest. In the lower layer, significantly smaller temperature increase was recorded. Slight temperature drops at the highest measuring point were worth of mentioning. It was connected with water evaporation from the surface grain layer.

From Fig. 3b it follows that at reversed placement of layers (W_l = 16% w.b., W_u = 8% w.b.) temperature increase was smaller. It is also evident that higher temperature values corresponded to higher moisture contents. Each day of measurement, temperature was lower in the higher parts of silo. Temperatures increased along with the storage time of grain. After 10 days, the maximum temperature in the lower part of the silo amounted to 30.5 °C, then it was gradually decreasing towards upper parts up to 22.5 °C.

Similar character of temperature changes was observed for rye (Fig. 4) and oat (Fig. 5). Higher temperatures were recorded for the first way of filling (lower layer with smaller moisture content than the upper). Process of self-heating for rye grain was significantly slower than for triticale. Maximum temperature in the upper part of the silo reached 25.5 °C. The highest temperatures were obtained during oat storage (after 10 days, temperature in the upper layer was 45 °C). In that case, temperature increase during storage amounted to 29 °C. The least increase was noted for rye grain (10.5 °C). Such large increase surely affects tensions in the silo wall and it influences the increase of difference between grain and outer temperatures. Therefore, such significant changes should be taken into account while designing a silo.

Studies proved that for all the cases temperature at the points localised along the silo axis were higher (by 2 °C) than that at side walls at the same measuring level.

Results for the material load are presented in Figs 6-8. Load on the cylindrical silo wall for all the studied cereals increased in all the measured layers along with the storage time. The highest load values were obtained for triticale, the lowest for oats. In most cases, maximum values occurred at the level of 275-475 mm. Figure 6a illustrates the course of triticale load changes at the lower layer initial moisture content W_l = 8% and moisture content of upper layer W_u = 16%. The highest pressure, measured just after bin filling (day 0) was 1.22 kPa. It occurred at the level of 275 mm. It increased up to 2.80 kPa after three, to 3.54 kPa after six, and to 3.80 kPa after ten days of storage. Index of load increment amounted to 3.1. With the converse layers arrangement (Fig. 6b, W_l = 16, W_u = 8%), the highest pressure was 1.35 kPa at the level of



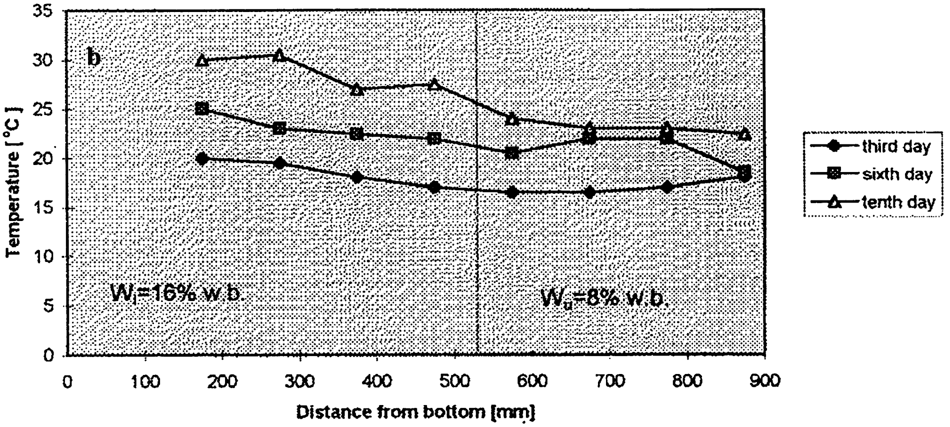


Fig. 3. Triticale temperature at the silo walls depends on the height and storage time: a) moisture content of the upper layer W_u= 16% w.b. and of the lower layer W_l = 8% w.b., b) moisture content of the upper layer W_u= 8% w.b. and of the lower layer W_l = 16% w.b.

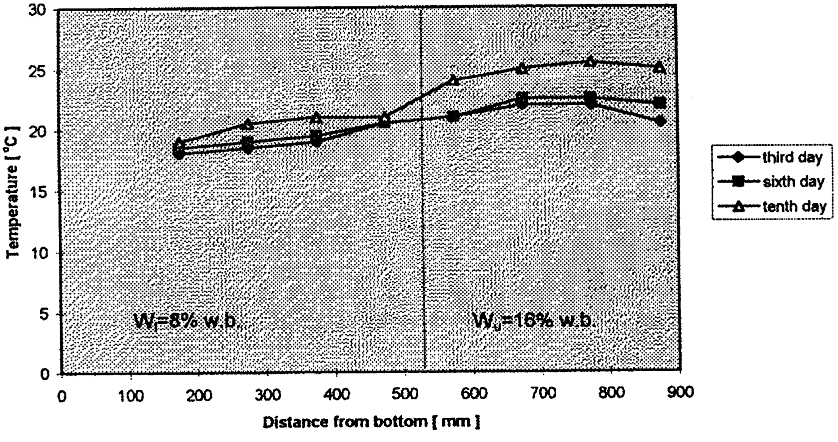


Fig. 4. Rye temperature at the silo walls depends on the height and storage time (moisture content of the upper layer W_u=16% w.b. and of the lower layer W_l=8%).

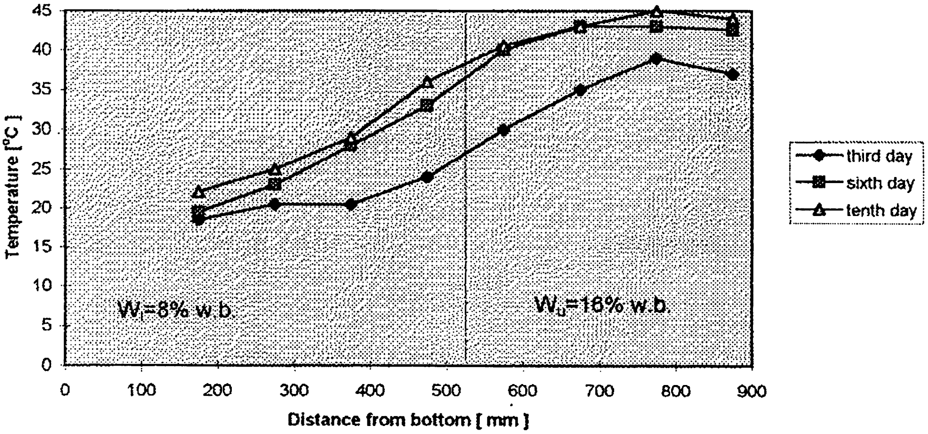


Fig. 5. Oat temperature at the silo walls depends on the height and storage time (moisture content of the upper layer W_u= 16% w.b. and of the lower layer W_l = 8% w.b.).

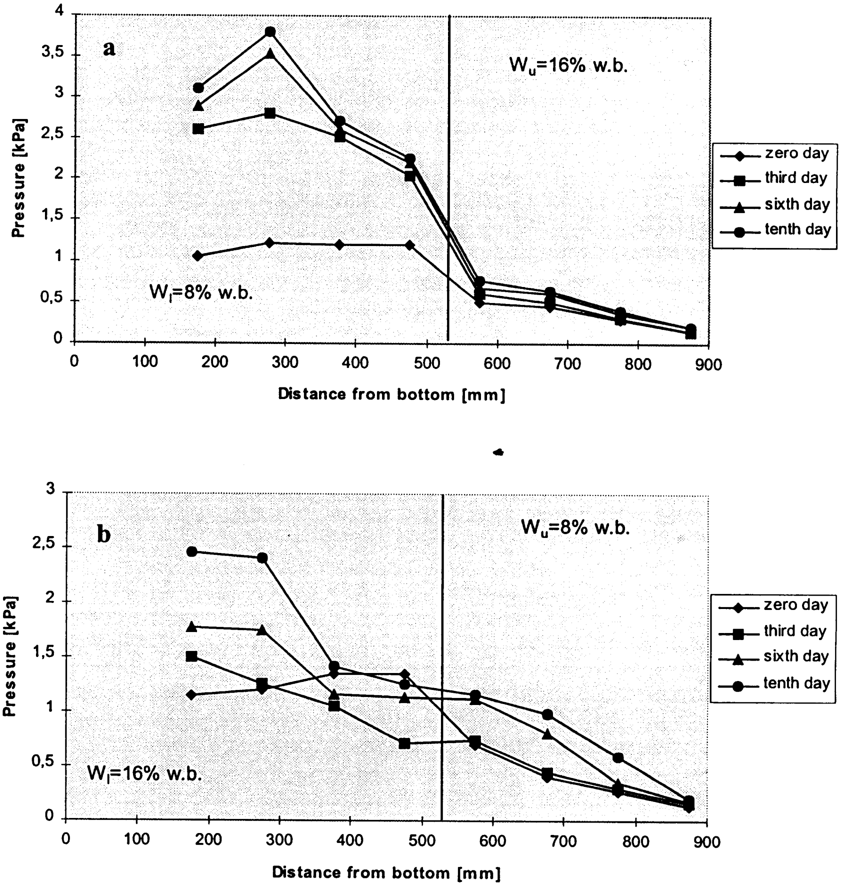


Fig. 6. Graph of the silo wall pressure - triticale grain: a) moisture content of the upper layer W_u=16% w.b. and the lower layer W_l=8%w.b., b) moisture content of the upper layer W_u=8% w.b. and the lower layer W_l=16%.

375 mm on the first day, but it appeared that the highest increments of the parameter value occurred in the lower part of the bin (at the level of 175 mm). After 3, 6 and 10 days, load amounted to: 1.50, 1.77, and 2.46, respectively. Slightly higher index (2.25) was observed at the level of 675 mm despite low pressure values (load increased from 0.4 to 0.99 kPa), which was associated with high hygroscopicity of dried grain.

With the first way of layer arrangement ($W_l = 8$, $W_u = 16\%$), other cereal loads were also higher than with the converse arrangement and they will be discussed further. The values obtained for rye pressure (Fig. 7) were lower than for triticale. The maximum load value on the silo wall for rye occurred at the level of 375 mm on day 0 and it amounted to 1.05 kPa. After 10 days it increased to 2.05 kPa (increment index 1.95). The highest loads were finally obtained at the level of 475 mm (2.25 kPa). At the level of 675 mm, the pressure increment index reached the value of 4.6, but the load changed only from 0.25 to 1.15 kPa. The process was affected by diffusion of water that was absorbed in the upper part of the bin. The lowest values of load were obtained for oat (Fig. 8). Its maximum values, in this case, occurred at the level of 375 mm (they increased from 0.60 to 1.88 kPa, increment index was 3.13). Despite low pressure values, similarly as for rye, high indices of pressure increment (3-3.2) were also obtained in the upper part of the silo at the levels of 675-875 mm.

From the presented data it is evident that during storage of rye, triticale or oat, temperature significantly increased which affected

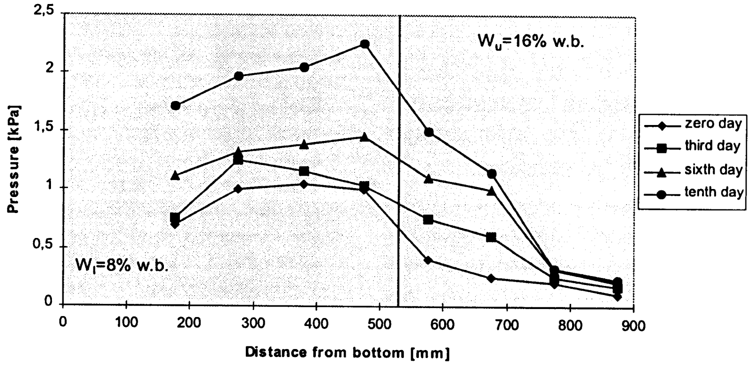


Fig. 7. Graph of the silo wall pressure - rye grain (moisture content of the upper layer W_u=16% w.b. and of the lower layer W_l=8% w.b.).

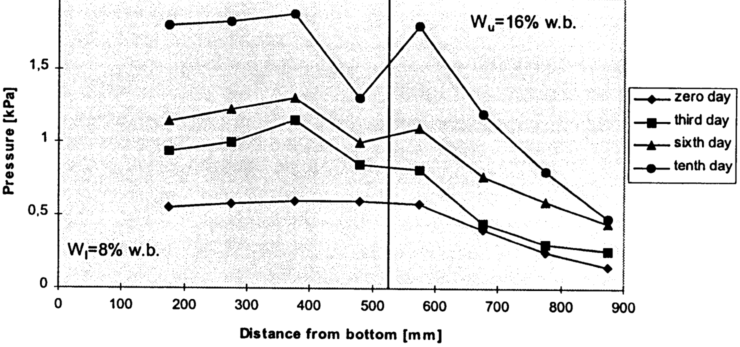


Fig. 8. Graph of the silo wall pressure - oat grain (moisture content of the upper layer W_u=16% w.b. and of the lower layer W_l=8% w.b.).

Table 1. Regression equations describing temperature and wall load

Material	W_u/W_l	Equation	Correlation coefficient
Triticale	16/8	$T=13.90+0.01012\mathrm{r}-0.0087H+0.78506t$	0.7634
	16/8	$P=0.8850-0.00104H-0.05552t$	0.9283
	8/16	$T=26.69+0.04832\mathrm{r}-0.00871H+0.80865t$	0.8893
	8/16	$P=0.3683-0.04937H+0.03771t$	0.8915
Rye	16/8	$T=15.89+0.00518\mathrm{r}+0.00219H+0.00249t$	0.8174
	16/8	$P=0.2437+0.00017H+ 0.03782t$	0.8237
Oats	16/8	$\mathrm{T}=12.73+0.00213\mathrm{r}+0.00505H+0.01109t$	0.8499
	16/8	$P=0.2338+0.00075H+0.09765t$	0.9128

where: T - temperature (°C), P - wall load (kPa), W_u - moisture content of the upper layer (%), W_l - moisture content of the lower layer (%), r - distance from the silo axis (mm), t - time (days), H - height (mm).

thermal loads arising in the bin wall and material loads on the wall increased, sometimes they were even several times higher. Both parameters can have the influence on the wall deformation.

The results obtained were subjected to variance analysis that proved that temperature and pressure values in the silo were strongly affected ($\alpha = 0.05$) by the type of cereal, storage time, height of the measuring point and arrangement of layers with different moisture contents.

The results were also subjected to regression analysis. Then it was possible to derive equations describing the studied parameters. The regression equations are presented in Table 1.

CONCLUSIONS

Moisture content of various grain layers during storage is related to the increase of its temperature and load on the bin wall.

Temperature and load values depend on the type of grain and the way layers are arranged.

Higher values of the studied parameters were obtained in the case of grain moisture content lower in the lower part of the silo than in the upper.

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