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HORIZONTAL PRESSURE ON THE WALL OF A MODEL SILO IN RELATION TO THE MOISTURE CONTENT OF OATS

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Summary. The paper presents results of measurements of the horizontal pressure exerted by the grains of oats, variety Dragon, on the wall of a model silo. Variable grain moisture levels i.e. 13.6, 19.0, and 25.0% d.b., at the initial temperature of 15°C were used in the experiments. The grains were stored over 21-day period. External temperature was controlled and established at the level of 20°C. It was found, that irrespectively of the initial grain moisture, the horizontal pressure increases over the storing period as the result of an increase in grain water content. The highest increase in the pressure was observed for the grains at highest moisture. The horizontal pressure was expressed in mathematical function of the water content, storage time, and distance from the silo bottom.

Key words: words: horizontal pressure, grain moisture, silo, storage time

INTRODUCTION

The value of grain pressure on the walls of a silo is related with the grain moisture content which varies with the duration of storage. This can be due to water diffusion resulting from differences in its concentration in the stored material, to water adsorption from the air – resulting from differences between air humidity and the grain moisture content, and to the absorption of water produced as a result of grain respiration [Blight 1986].

Wratten *et al.* [1969], Muthukumarappan *et al.* [1992], Deshapande *et al.* [1993], and Mohsenin [1986] found that grain swells during wetting, and the increase in the grain volume is directly proportional to the amount of the absorbed water.

Wratten *et al.* [1969] assumes a grain volume increase of $1.0 \cdot 10^{-5}$ $m^3 \cdot kg^{-1}$ of dry mass per every percentage point of moisture content increase. This level of volume increase is comparable with experimental results; eg. Mohsenin [Kusińska 2003] obtained a volume increase of $1.03 \cdot 10^{-5}$ $m^3 \cdot kg^{-1}$ of maize dry mass; Muthukumarappan *et al.* [1992] obtained $9.49 \cdot 10^{-6}$, $0.04 \cdot 10^{-6}$ and $8.9 \cdot 10^{-6}$ $m^3 \cdot kg^{-1}$ of dry mass for unpolished, brown and crushed rice, respectively. The true increase in grain volume may be lower, especially at low levels of grain moisture content, due to the effect of surface sorption [Mohsenin 1986].

Increases in grain volume cause a considerable increase in the hygroscopic pressure. An example of this can be found in the studies by Dale and Robinson [1954], who studied pressures in a silo 1.5 m high and 0.46 m in diameter. They filled the silo with maize grain and supplied humid air. When the grain moisture content increased from 13 to 17%, they observed that the hydrostatic pressure at the bottom of the silo increased from 2.1 kPa to 13.5 kPa.

Britton *et al.* [1993] monitored the vertical forces acting on silo walls in the process of wetting grain with humid air. Their model silo, 1.5 m high and 1 m in diameter, was filled with wheat grain with an initial moisture content of 10%. They found that forcing humid air of a temperature of 23°C through the grain mass for about 900 minutes caused total disappearance of friction against the walls. Gravity acting on the grain mass was completely counterbalanced by the force of lateral pressure of the swelled grain. This occurred at a 6% grain moisture content increase. The grain swelling resulted in the appearance of strong pressures against the walls and a reduction of pressure against the bottom of the silo.

The process of water absorption causes a change in grain density. Grain density decreases with increasing moisture content, due to increased grain volume. Functional relationships between grain mass density and changing moisture content have been presented, in the form of compound equations, by Zhang and Britton [1995]. Mühlbauer and Scherer [1977] suggested the linear relation for the description of the relationship between density and water content for maize grain.

Zhang and Britton [1995] developed a theoretical model for the calculation of silo structure loads caused by the hygroscopic phenomena. The model assumes that the increase in individual kernel volume is proportional to the amount of the absorbed water. Pressure values, calculated by means of the model, corresponded within 3% with the empirical data. For a hypothetical silo, 6.15 m high and 4.2 m in diameter, the calculated index of pressure increase was from 5.0 to 8.6 with a 10% increase in maize grain moisture content (for maize grain with bulk density of 618 and 771 $kg \cdot m^{-3}$, respectively).

Grochowicz *et al.* [1998] conducted a laboratory study using a model silo. The study involved measurements of changes in the moisture content, temperature and lateral pressure caused by water diffusion in barley grain. The factor causing water transfer was the difference in its concentration in two grain layers (moisture content of one layer was 10%, and the other – 16%). Greater changes in the lateral pressure were observed when the initial moisture content of the lower layer was higher than that of the upper layer. With the reverse arrangement of the grain layers the changes were less pronounced, though still statistically significant. Increased lateral pressure of the grain was accompanied by higher levels of the moisture content and barley grain temperature.

Comparative studies on hygroscopic pressures caused also by water diffusion, performed for wheat, barley, oats and triticale grain, were conducted by Kusińska [1998, 1999, 2002, 2003, 2004]. She found a relationship between the pressure values and the kind of grain, its physical properties, and the duration of storage. As a result of filling a silo with a variable grain moisture content, the greatest increase in horizontal pressure values was observed for triticale grain, and the lowest for oats. She also observed an excessive accumulation of water at the lower parts of the silo and on the cover. This sparked her interest in the problem of the effect of high moisture content levels on the values of grain pressure in silos.

MATERIAL ANAD METHODS

The objective of the study was to measure, on a stand, the horizontal pressures exerted by dry oats grain (moisture content of 13.6% d.b.), and to compare the results with corresponding data for wet grain (moisture contents of 19.0 and 25% d.b.). The required moisture content in the grain was achieved by watering. An adequate quantity of water was added which was calculated by the equation:

$$M_w = M_g \frac{u_2 - u_1}{100 + u_2} \tag{1}$$

where:

M_w – volume of added water into the grain, kg,
M_g – mass of watering grain, kg,
u_1 – initial grain moisture content, % d.b.,
u_2 – required grain moisture content, % d.b.

The grain was mixed and stored in a densely closed barrel at 72 hours at 15°C. It was rotated around to balance moisture content every few hours. Before filling the silo, the moisture content was controlled.

The study was conducted on a test stand, as presented in Figure 1. The basic element of the stand was a silo (1) of inner diameter of 0.6 m and 1.2 m height. The silo was provided with a thermostatic jacket, supplied with water from an ultra-thermostat (6). The silo wall pressure was measured at eight levels (located at 0.175, 0.275, 0.375, 0.475, 0.575, 0.675, 0.775 and 0.875 m from the bottom edge of the cylindrical part of the silo) by means of strain gauges (2) and an electronic indicator (5) The measurement was made with strain gauge type AR 201 force of measuring range 2 N. The force was proceeded on the piston diameter of 25 mm and it was read on the amplifier display, type AR 923 at the measuring accuracy of 0.01 N. Horizontal pressure P_h was estimated by the equation:

$$P_h = \frac{F_h}{S} \tag{2}$$

where:

P_h – horizontal pressure, Pa,
F_h – horizontal force, N,
S – piston's surface, m^2.

The measuring system was calibrated by the static method before every bath of the silo. The pistons were separated from the grain with a thin-rubber membrane.

The silo was filled with oats grain with a specific moisture content. Then the silo was tightly closed with the cover, and the grain pressure against the walls of the silo was measured once a day, at a constant time. After 21 days the grain was poured out. All measurements were taken in three replications at a constant temperature of the water jacket 20°C.

The design of the measurement set-up allows grain temperature to be measured by means of thermocouples (3) connected to a temperature gauge (4).

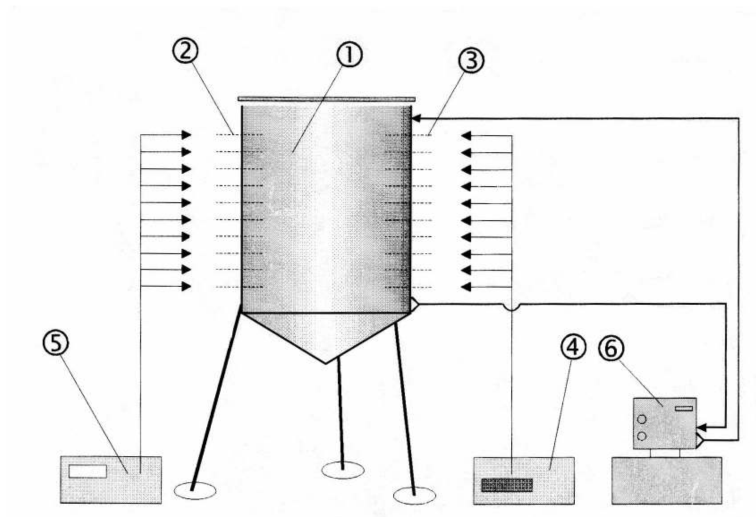

Fig. 1. Schematic diagram of the measurement apparatus: 1 – silo, 2 – strain gauge, 3 – thermocouple, 4 – digital temperature gauge, 5 – electronic wall pressure indicator, 6 – ultra-thermostat

RESULTS

Horizontal pressure on the silo wall, at the constant external temperature of 20°C, changed during the process of oats storage. Results of measurements for grains stored within the variable initial water content (13.6, 19.0, 25.0% d.b.) are presented in Figures 2–4. The pressure values were related to the place of measurement taken (in respect to the silo height measured from the bottom edge of the cylindrical part of the silo, as described in the previous section)

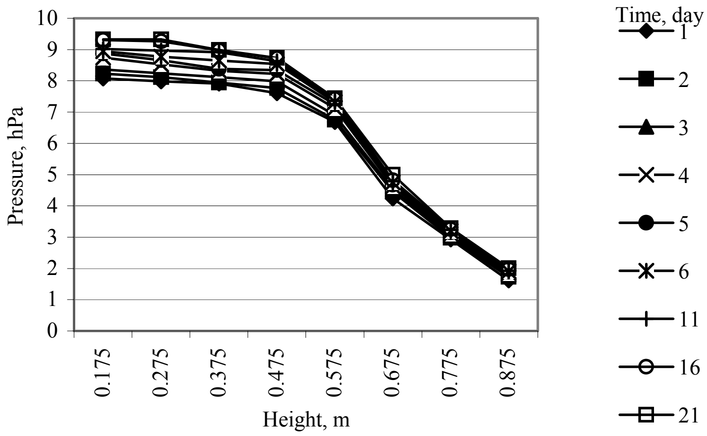

Fig. 2. Horizontal pressure on a silo wall exerted by the grains of oats at 13.6% d.b. of water content in relation to the measurement position and time of storage

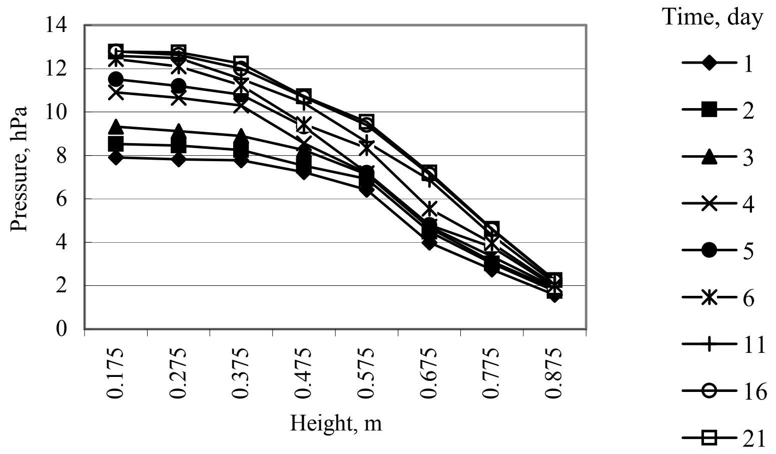

Fig. 3. Horizontal pressure on a silo wall exerted by the grains of oats at 19.0% d.b. of water content in relation to the measurement position and time of storage

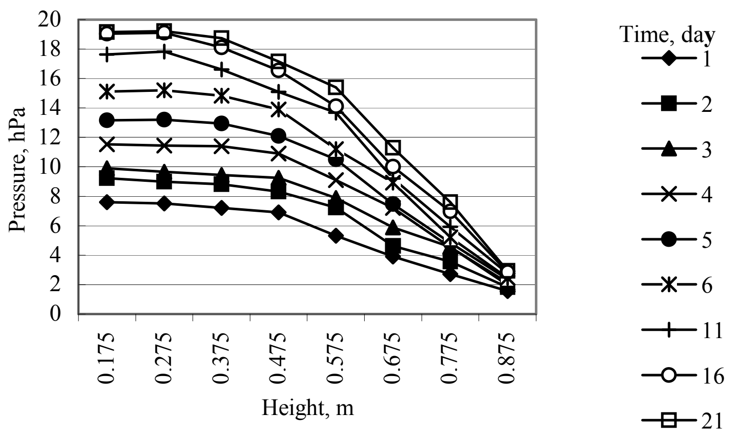

Fig. 4. Horizontal pressure on a silo wall exerted by the grains of oats at 25.0% d.b. of water content in relation to the measurement position and time of storage

The highest pressure values at the beginning of experiments, were observed for grains at the lowest initial moisture level. They were also lower at the higher water contents (19.0 and 25.0% d.b.), and were equal to 7.91 and 7.59 hPa respectively (Fig. 3 and 4). It was related to the decrease in grains bulk density, that corresponds with higher moisture levels [Kusińska 2002, 2004]. The observed increase in values of the horizontal pressure was due to the biological processes occurring during the grain storage (at the 15°C of initial temperature) over the 21-day period at the ambient temperature of 20°C. It was also dependent on the water content. The horizontal pressure exerted by the grains mass of initial moisture 13.6%, over the same 21-day period, increased slightly – with the maximum about 9.32 hPa (Fig. 2). High moisture levels i.e. 19.0 and 25.0% d.b. induced the increase in pressure up to 12.78 and 19.16 hPa, respectively. It was observed at the height 0.175 m of cylindrical silo part.

The obtained research results were statistically analysed. The analyses showed that the horizontal pressure exerted by the grains of oats, $P_{h,}$ is significantly influenced (at $\alpha \leq 0.01$) by the water content, *u*, storage time, *τ,* and distance from the silo bottom part, *h*.

The following relation was derived by the means of the nonlinear multiple regression method (R^2=0.87):

$$P_h = 24.86 + 0.55\tau - 31.27h + 0.0078u^2 - 0.016\tau^2 + 8.09\ln h \qquad (3)$$

The mean values of the horizontal pressure on the silo wall in relation to the water content of oats and storage period is presented in Fig. 5. For the 13.6% of moisture, they changed only slightly (from 5.88 to 6.76 hPa), and were mainly caused by the change in grain packing structure, and less by the increase in water content. The moisture contents of 19.0 and 25.0% d.b. attributed to the increase in the average pressure from 5.68 to 9.01, and from 5.33 to 13.94 hPa, respectively.

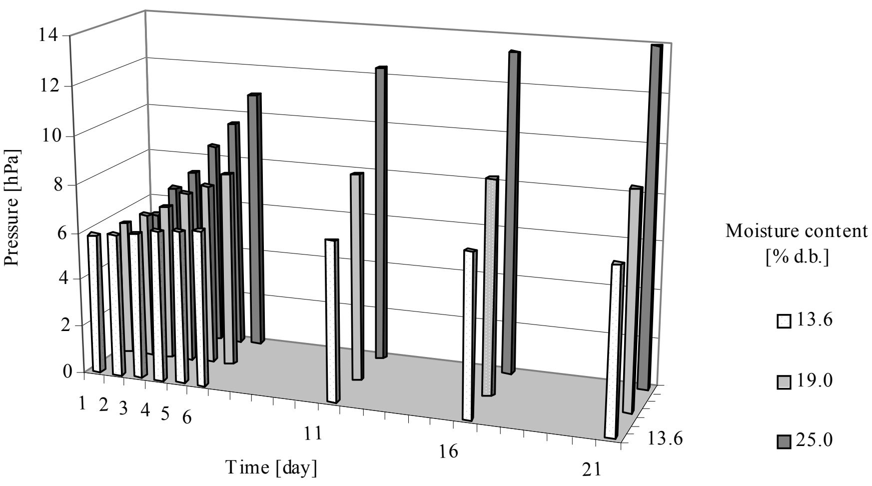

Fig. 5. Mean values of the horizontal pressure on a silo wall exerted by the grains of oats in relation to the moisture content and time of storage

The highest values of the horizontal pressure, within the moisture levels tested over the whole period of experiments, were mainly noticed at the 0.175 m silo height. However, for wet grains at the 25.0% of moisture, slightly but not significantly higher values of the pressure at the height 0.275 m in comparison to 0.175 m were noticed after the fifth day of storage. At these silo heights levels, a rate of pressure increase for 13.6, 19.0, 25.0% d.b. of the initial moisture contents was equal to 1.15, 1.61, and 2.55 respectively. These high increases in pressure values were mainly caused by grain swelling, as the results of water absorption produced during grain respiration. The horizontal pressure values on the silo wall at 0.175 m height are presented in Fig. 6.

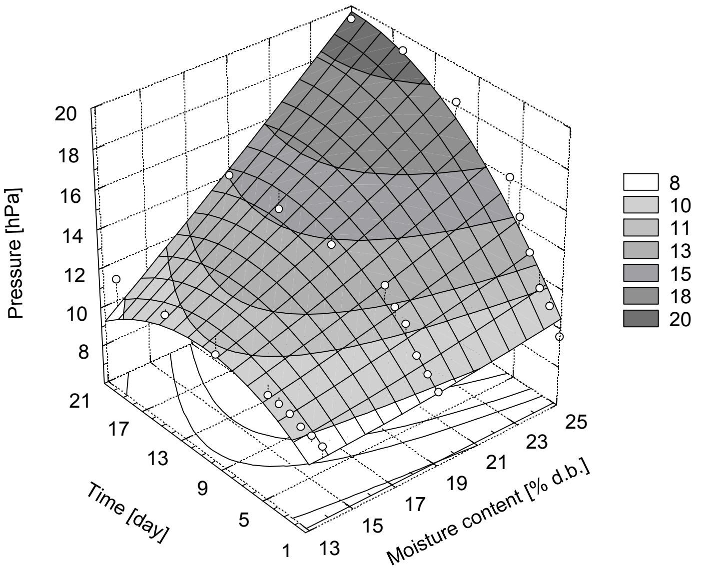

Fig. 6. Horizontal pressure of grains of oats on the silo wall at 0.175 m height

The above dependency was described by the following multiple regression equation with $R^2=0.89$ at $\alpha \le 0.01$:

$$P_h = 0.0049u^{2.24} + 4.1\tau^{0.31} \tag{4}$$

During the storage of grains at 25.0% d.b moisture, grain bridging in the silo was observed, due to the high rate of increase in the horizontal pressure at the bottom part of the silo, caused by the 2.05% increase in grain water content.

The results of the presented experiments confirm observations of Zhang and Britton [1995], which stated that an increase in hygroscopic pressure is related to grain density. They observed 5 to 10 kPa increase in pressure values corresponding to the one percent rise in moisture for maize. In the present study, this increase was lower and equal to about 5,64 hPa. It is due to smaller sizes of the bin.

CONCLUSIONS

The presented results allow to state the following:

1. Horizontal pressure changes over the storage period of oats in moist as well in dry state. It results from the water absorption produced during grain respiration processes, and grain swelling.

2. Mean values of the horizontal pressure on the silo wall are significantly higher for the moist grains in comparison to the dry ones.

3. During the storage of grains at 25.0% d.b. moisture, grain bridging in the silo was observed.

4. An increase in grain moisture content, as well as time of storage, have a negative influence on the pressure in the silo. They cause its significant increase.

5. An increase of 2.05% in grain moisture content in the bottom part of the silo caused the 11.57 hPa rise in the horizontal pressure.

REFERENCES

Blight G.E. 1986: Swelling pressure of wetted grain. Bulk Solids Handling, 6(6), 1135–1140.

Britton M.G., Zhang Q., McCullagh K. 1993: Moisture induced vertical loads in model grain bin. ASAE Paper No. 93-4503, St. Joseph, Mich., ASAE.

Dale A.C., Robinson R.N. 1954: Pressure in deep grain storage structures. Agric. Eng., 35(8), 570–573.

Deshpande S.D., Bal S., Ojha T.P. 1993: Physical properties of soybean. J. Agric. Eng. Res., 56, 89–98.

Grochowicz J., Kusińska E., Bilański W.K. 1998: Mass exchange in adjacent layers of grain material stored in silo. Int. Agrophysics, 12(2), 103–108.

Kusińska E. 1998: Effect of moisture content of cereal grains layer on pressure distribution on silo wall. Int. Agrophysics, 12(3), 199–204.

Kusińska E. 1999: Effects of moisture content of grain layers and their configuration in a silo on temperature and pressure distribution. Int. Agrophysics, 13(4), 469–476.

Kusińska E. 2002: Wpływ zawartości wody i temperatury ziarna pszenicy na napór poziomy w modelowym silosie. Rozprawy Naukowe Akademii Rolniczej w Lublinie, Wydział Techniki Rolniczej, 255.

Kusińska E. 2003: Influence of outer energy on rye grain temperature distribution in model silo. Teka Kom. Mot. Energ. Roln., V(III), 147–155.

Kusińska E. 2004: Wpływ czasu przechowywania, zawartości wody i samozagrzewania na wybrane parametry geometryczne ziarna owsa. MOTROL, Mot. i Energ. Roln., 6, 138–145.

Mohsenin N.N. 1986: Physical Properties Of Plant And Animal Materials. 2nd ed., New York, Gordon and Breach Science.

Muthukumarappan K., Jindal V.K., Gunasekaran S. 1992: Volumetric changes in rice kernels during desorption and adsorption. Trans. ASAE, 35(1), 235–241.

Mühlbauer W., Scherer R. 1977: Die Spezifische Wärme von Körnerfrüchten. Grundl. Landtechnik, 27, 33–40.

Wratten F. T., Poole W.D., Chesness J.L., Bal S., Romarao V. 1969: Physical and thermal properties of rough rice. Trans. ASAE, 12(6), 801–803.

Zhang Q., Britton M.G. 1995: Predicting hygroscopic loads in grain storage bins. Trans. ASAE, 38(4), 1221–1226.