Int. Agrophysics, 2001, 15, 247-254

INTERNATIONAL
Agrophysics
www.ipan.lublin.pl/int-agrophysics

Effect of the triticale grain moisture content on the spontaneous heating of grain and on the pressure against the silo wall

E. Kusińska

Department of Engineering and Machinery, University of Agriculture, Doświadczalna 44, 20-236 Lublin

Received October 9, 2000; accepted May 29, 2001

A b s t r a c t. The author presents the results of studies on the temperature and horizontal pressure of triticale grain in a model silo. The studies included grain with an initial moisture content of 13, 16 and 18% w.b. The grain storage duration was 25 days. The study showed that grain temperature is affected by its initial moisture content. The highest temperature values were observed in grain with an initial moisture content of 18% w.b. Also, a higher initial moisture content results in greater increases in pressure.

K e y w o r d s: triticale, moisture content, silo, heating

INTRODUCTION

Temperature and moisture content are the most important factors affecting grain quality in the course of its storage. Seasonal and diurnal variation in temperature have a negative effect on stored grain, cause water migration and changes in its distribution within the material stored. The accurate prediction of moisture content and the temperature of grain in storage is necessary for the effective control of the process of ventilation, applied to provide optimum storage conditions for grain and the minimizing of conditions for infestation by insects [2].

The free migration of water depends on a number of factors - the kind and quality of grain in storage, the size and shape of the grain, its temperature, initial moisture content, and atmospheric conditions. It also depends on the duration of storage, as well as on the sorptive and diffusive properties of the grain. Those factors cause the process of water migration to be unstable. Water tends to migrate from warmer to cooler areas within grain mass. The migration rate is faster in grain with a higher moisture content than in dry grain [10].

EFFECTS OF WATER MIGRATION IN PLANT MATERIALS

Numerous authors have tried to describe the phenomenon of water migration. Holman and Carter [10] studied the process in over a dozen soybean varieties with different bean sizes. They showed that water migration takes place in all soybean varieties, which results from water accumulation in higher layers of material in storage. Schmidt [19] conducted experiments involving measurements of the wheat grain moisture content during storage. He found that water migration generally begins in the second half of September or at the beginning of October.

Hellevang and Hirning [9] performed a study on 16 varieties of beans of various sizes during the period from April to August. They observed an average moisture content drop by 2.56% in the upper layer and a 0.45% increase in the layer located 0.6 to 1.8 m below.

Knowledge of changes occurring in the course of cereal grain storage is very important for practical purposes. The application of a suitable model for the calculation and determination of the quantitative and qualitative distribution of water and temperature within the grain mass in storage, the grain being a commercial commodity, can help the proper storage of various cereals under a variety of climatic conditions.

A numerical model for the calculation of water migration within grain mass in storage has been developed by Khankari [11]. He derived non-linear equations describing the temperature, moisture and rate of free convection, using current weather data. The numerical model for the calculation of water

Author's e-mail: kusinska@faunus.ar.lublin.pl

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migration was used for the calculation of temperature and moisture distribution in grain, for conditions prevalent in Minnesota. The model was based on the assumption that natural air convection is the prevalent phenomenon within grain mass. The mathematical model was then tested experimentally [13]. For the tests, Khankari used a cylindrical silo, 10 m high and 10 m in diameter, in which he stored maize grain with an average moisture content of 14% at an average temperature of 25°C for the period of one year, beginning from October, without ventilation. Values of thermal conductivity calculated by means of the model conformed to the results of the experiment. Khankari *et al.* [12] also gave the values of the other parameters of diffusion for maize grain. They found that water migration increases with increasing temperature. During the initial period of storage, i.e., during the autumn rainy period and early winter, water migration is limited to areas close to the silo walls. The effect of natural convection on water flow appears at the end of December and at the beginning of January, when temperatures reach the maximum levels. Therefore, water migration rate is the fastest in winter. The studies showed that the increased thermal conductivity of grain has a limiting effect on natural air convection, and that water migration takes place in silos of all sizes, though it begins earlier in smaller silos. Cooling the grain down to 0°C in the autumn permits its moisture content to be kept stable throughout the year.

Lo *et al.* [17] used Chen's and Clayton's equation for the simulation of radial changes in the moisture content of wheat grain stored in a concrete silo. The equation was based on the assumption that moisture content changes are only related to temperature.

Thompson [20] and Fan *et al.* [3] were involved with modeling the process of ventilation. Thompson [20] developed a model representing temperature changes of grain in storage, its moisture content, and dry mass distribution. He arrived at the conclusion that a true balance between the air and the grain is possible to maintain when the grain is ventilated with ambient air at low flow rates.

Fan *et al.* [3] studied water diffusion in various varieties of wheat. They found that the coefficient of water diffusion in wheat grain can be expressed in the form of an opposite to the exponential function of absolute temperature, and the coefficient does not change its value for hard wheat within the temperature range of 26-54°C. They determined the coefficients of diffusion for several wheat varieties within a temperature range from 26 to 98°C. The values spanned a range from 2×10^{-12} to 245×10^{-12} $m^2 s^{-1}$, depending on the temperature and the wheat varieties.

Chang *et al.* [2] maintain that the average moisture content of grain stored during time $t + \Delta t$ is:

$$W_u = W_0 + \left(H_0 - H_u\right) M_r \qquad (1)$$

where: W_u - average moisture content in the grain layer, final or subsequent simulation for Δt period, kg kg^{-1} (decimal, d.b.); W_0 - moisture content, initial or prior to simulation for Δt period, kg kg^{-1} (decimal, d.b.); H_0 - humidity ratio of ambient air, kg kg^{-1}; H_u - humidity ratio of air leaving the grain layer, kg kg^{-1}; M_r - mass ratio of inlet air to the dry grain during Δt.

Chang *et al.* [1] studied wheat grain with an initial moisture content of 11.8%, stored in silos 6.6 m high and 4.2 m in diameter. On the basis of the studies, they concluded that the simulation values of the grain moisture content coincided with the gain moisture values measured during a period of 15 months and that the moisture content in the layer close to the surface decreased by 2 to 2.5% during the summer months, while in the central and bottom parts of the silos, the changes in grain moisture content were only slight.

Modeling of temperature and the moisture content of rice stored in silos was the subject of interest for Freer [4], and Haugh *et al.* [8]. Haugh *et al.* [8] conclude that grain temperature is the most important parameter in grain storage and should be maintained at 10-15°C irrespective of the broad range of the grain moisture content levels. According to those authors, grain temperature is the most significant, though grain moisture content is also very important.

According to Freer *et al.* [4], the air temperature around the silo should be known in order to calculate the temperature differences between the grain in the silo and the ambient temperature. They presented equations for the calculation of the mean diurnal temperature for the year, taking into account the latitude, and for the determination of the moisture content of unpolished rice, as well as of dry mass losses. The experimental part of their study was performed by mans of a two-dimensional model which they used to analyze changes in temperature and moisture content, the level of dry mass losses, and the level of water condensation. In their study they used initial grain temperatures of 10, 20 and 30°C, moisture content levels of 11, 13 and 15%, and three charging times. In the test program they assessed the initial temperature of grain, the initial grain moisture content, and the charging time (the time of filling the silo with grain). Observations were conducted for 12 months. The charging time was found to have had little effect on the parameters under study. Relatively high losses of dry mass were observed at grain temperature of 30°C at 15% initial moisture content. High initial temperatures and moisture content levels had a significant effect on water migration towards the top of the silo, which means that the top area is more conducive to the grain turning bad and to increased microbial activity.

Increased grain temperature causes an increase in the pressure exerted by grain on the walls and bottom of silos. The effect of the properties of the material stored (sand, shelled maize, wheat, and sorghum) on lateral pressures induced thermally were studied by Puri *et al.* [18]. The results of the experiments indicate that thermally induced stress in storage tanks depends on the bulk density of the material stored. To calculate the thermal overpressure (P_t) as a function of temperature drop (ΔT) they used linear equations:

$$P_t = C_p(\Delta T) \quad (2)$$

where C_p - thermal pressure coefficient (kPa °C^{-1}).

Zhang *et al*. [21,23,25] improved the model for the prediction of loads in silos caused by thermal phenomena in the course of grain storage. The new model was developed using finite element analysis. It was based on the elasto-plastic theory developed by Lade [14] and Zhang *et al*. [22]. The theoretical results were tested by the authors experimentally, by measuring the thermally induced stress in the casing of a cylinder made of aluminum sheeting 0.8 mm thick (0.9 m in diameter and 1.2 m high) and filled with wheat grain. In their experiments they applied three full temperature change cycles within the range of 32-22°C. Stress values were measured at three levels. The authors studied the effect of the cycle order and temperature change on the coefficient of lateral pressure C_p. The mean, for the three levels, increase in pressure, with dropping temperature, was 0.22 kPa °C^{-1} in the first cycle, 0.36 kPa °C^{-1} in the second, and 0.38 kPa °C^{-1} in the third, while with increasing temperature the corresponding values were 0.38, 0.40 and 0.41 kPa °C^{-1}, respectively. The authors concluded that the relationship between the lateral thermal pressure and the temperature change was linear, and that the pressures during temperature increase were 72.2, 11.1 and 7.8% higher than in the case of the dropping temperature in the first, second and third cycles, respectively.

Another model of granular material in storage, which took into account loads induced by silo walls, as well as the silo wall-grain and silo bottom-grain interfaces, was presented by Zhang *et al*. [25]. That model did not reflect changes in temperature. Therefore, Li *et al*. [16] expanded a new version of the model based on finite element analysis by including values characteristic for the material stored within the range of average temperatures. The model was tested on wheat grain with an initial moisture content of 10% and a bulk density of 825 kg m^{-3}. The silo with the wheat grain was subjected to cyclic temperature changes between 32 and 22°C with an amplitude of 10°C per h. After the application of an additional loading of 40 kPa, the grain was let rest for 2 h. They tested additional grain loading at various depths, which permitted the determination of the silo wall deformation [23]. The two-hour period of rest allowed the grain to attain a stable state of stress - measuring instruments did not record any changes of strain in time. Tests performed on the empty silo showed that no deformation occurred in the upper and the lower parts of the silo [15].

Zhang *et al*. [24] studied the changes in the value of pressure quotient k in relation to the distance from the silo axis and the grain layer depth under the effect of static and thermal loads in shallow and deep silos. They analyzed stress in cylindrical grain silos using the model of second generation. They applied the analysis to two grain silos: one with a diameter of 3 and 9 m high, and another of 9 m in diameter and 9 m high. Both were made of corrugated sheet-metal and filled with wheat grain with 10% moisture content and an initial bulk density of 801 kg m^{-3}. In both cases they determined the main direction of stress within the grain mass and the ratio k of lateral to vertical pressure. They found that neither the lateral nor the vertical static pressures were uniform, but decreased in the direction from silo axis towards the walls. Lateral thermal pressures increased with the increasing distance from the silo axis, while the vertical thermal pressures decreased. The lateral pressure increased more than the vertical when the grain temperature dropped to 30°C. The lateral pressure increase close to the silo wall was much stronger than that at the silo axis when the temperature dropped to 30°C. Changes in the k ratio value were slight, irrespective of the distance from the silo axis in the case of static loads, but increased to 20-63% with the thermal loads. Changes in the k ratio value were slight when referenced to the grain layer depth in static loading, but decreased (by an average 20%) from the top to the bottom of the silo in thermal loading. The average thermal values of k were higher than the static.

Silos are usually filled with grain of a varied moisture content. Grochowicz *et al*. [5] and Kusińska [6,7] studied the effect of the grain layer moisture content on the distribution of temperature and water, and on the pressures exerted by the grain on the silo walls. They showed that interlayer differences in the grain moisture content cause strong increases of grain temperature and pressures exerted on the silo walls at the interlayer boundaries.

The problems presented above indicate the strong need for studies on grain temperature and moisture content, and on the effect of those factors on pressures acting on structural elements of silos. Changes in pressures can be caused not only by changing external temperature. They are also strongly affected by the initial moisture content of the grain, as this affects the process of microorganisms and insect evolution, causing increased temperature and moisture content.

SCOPE AND METHOD

The study presents the results of model investigations involving measurements of pressure acting on silo walls and grain temperature. The material used was triticale grain with initial moisture content levels of 13, 16 and 18% w.b., stored at a constant external temperature of 15°C for a period of 25 days. A moisture content of 13, 16 or 18% w.b. was achieved by the addition of adequate water volume and was calculated by the equation:

$$M_w = M_g \frac{w_2 - w_1}{100 - w_2} \quad (3)$$

where: M_w - volume of required water addition to achieve the moisture content of w_2, kg; M_g - mass of watered grain, kg; w_1- initial grain moisture content, % w.b.; w_2- required grain moisture content, % w.b.

Watered grain was stored in a tightly closed barrel for 72 h. It was rotated every few hours to equalize the moisture content. Before starting the test, the moisture content was controlled.

A schematic diagram of the test stand is presented in Fig. 1. The main element was the silo (1) which was provided with a water jacket. The external diameter of the silo was 600 mm and its height was 1200 mm. The water jacket was supplied with water at a required temperature, the water temperature being controlled by means of an ultra-thermostat (6). The silo was filled with triticale grain of a specific initial moisture content. In all the experiments the initial grain temperature was the same at 15°C. Then, the initial pressure against the silo wall was measured at eight height levels above the silo bottom (175, 275, 375, 475, 575, 675, 775 and 875 mm). During the experiments, the pressure values were measured once a day by means of strain gauges (4) and a force gauge type APAR AR 923 (5). At the same time the grain temperature inside the silo was measured at 40 measurement points by means of thermocouples (2) and a temperature gauge type AR 592 (3). The temperature measurement points were located at the same height as the strain gauges, at distances from silo axis of 0, 75, 150, 225 and 300 mm. Strain gauges at a measuring range of 1 and 2 N and a measuring accuracy of 0.01 N were used. Steel pistons with a diameter of 25 mm were attached to the gauging point and

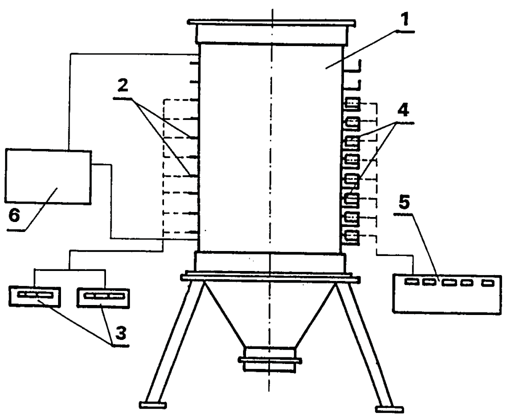

Fig. 1. Schematic diagram of the test station. 1 - silo, 2 - thermocouples, 3 - temperature gauges, 4 - strain gauges, 5 - silo wall load indicator with amplifier, 6 - thermostat.

the grain was pressurized through a thin-rubber membrane. It was calculated by the equation:

$$P = \frac{F}{S} \quad (4)$$

where: P - grain pressure on the wall, Pa; F - grain pressure force, N; S - pistons surface, m^2.

The strain gauges were attached to the wall with the bracket. The measuring system was calibrated by a static method before every bath of the silo. Temperature measurement was carried out to within an accuracy of 0.1°C.

All measurements were taken in three replications.

RESULTS

The mean values of the pressure and temperature measurements are presented in Figs 2 and 3. In all cases the initial temperature of the triticale grain put in the silo was 15°C. In the course of storage, the grain temperature reached the highest values at the silo axis, and that is why the diagrams illustrate temperature changes at measurement points located along the axis. The temperature of triticale grain with an initial moisture content of 13% w.b. increased with the passage of storage time. The strongest increase in temperature was observed at measurement points located at the height of 675 and 775 mm above the silo bottom. After 25 days, the grain temperature at those levels was 22°C. A much higher increase in grain temperature was recorded for the triticale grain with an initial moisture content of 16% w.b. (Fig. 2). The strongest changes in temperature occurred during the period up to day 20 of the storage. At a height of 675 mm the temperature value reached 36°C and the lowest measurement point - 30°C. Between day 20 and day 25, changes in temperature were only slight. The temperature increased by 2 degrees, mainly in the lower part of the silo. The highest temperature values were observed in the case of the triticale grain with the initial moisture content of 18% w.b. (Fig. 2). The maximum value observed after 25 days was at a height of 675 mm (44°C). At that time the temperature at the bottom of the silo was 36°C. At this moisture content, the temperature increase was also the strongest until day 20 of storage.

In all the experiments the temperature at the highest measurement level was lower than at heights of 675 and 775 mm. This was due to water evaporation. The fact that the highest temperatures were observed at heights of 675 and 775 mm indicates water diffusion from the bottom towards the top of the silo, and its absorption (mainly) at those levels. Temperature at the silo wall was lower than at points located on the silo axis (after 25 days of storage by an average of 2-5°C depending on the grain moisture content). The mean value of triticale grain moisture content increased by 0.5% in the first case, 1.2% in the second, and by about 2.1% in the third.

Increased moisture content caused changes in the value of pressure on the silo wall. The lowest increases in silo wall

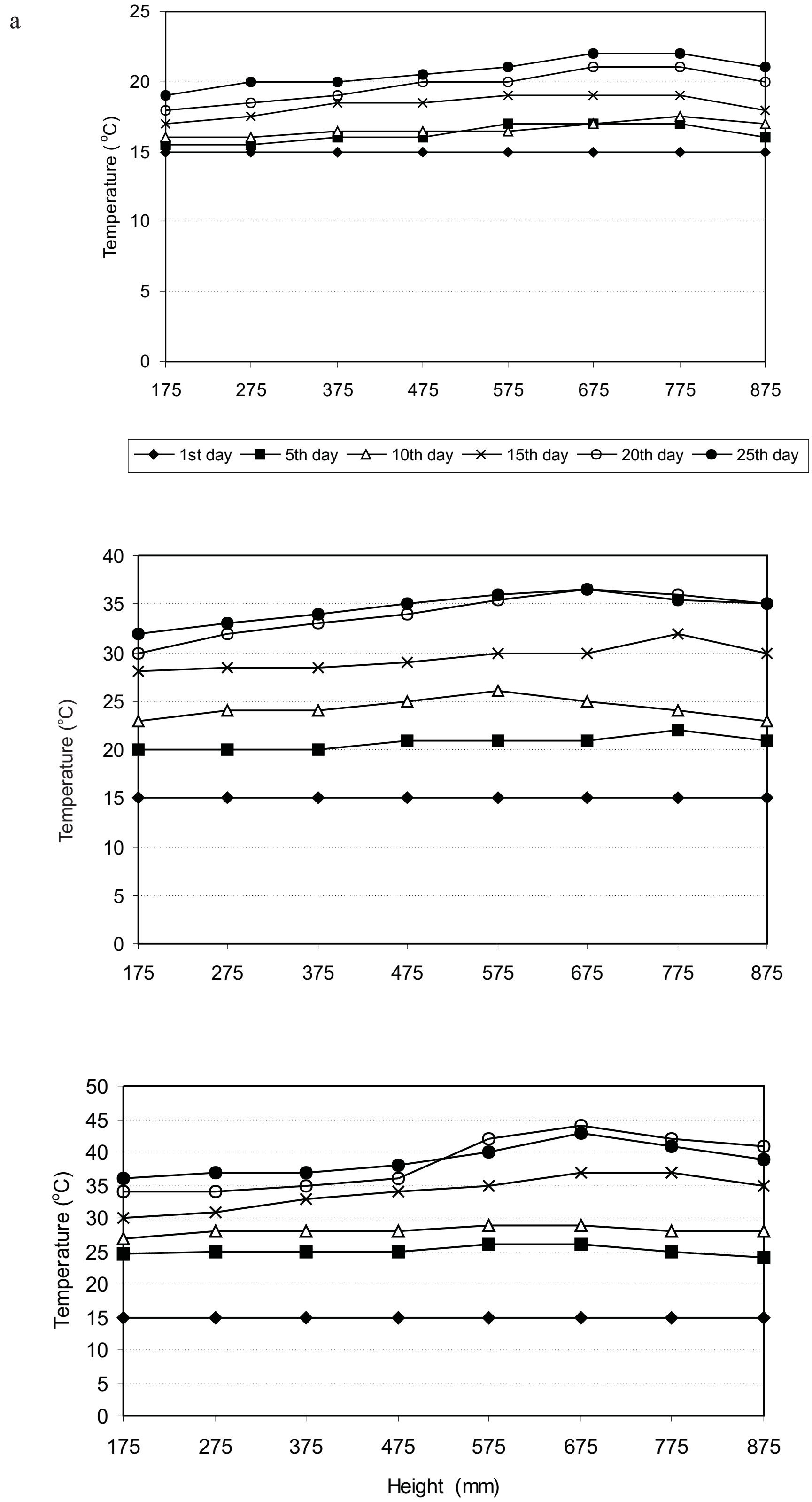

Fig. 2. The effect of storage duration on the temperature of triticale grain with moisture content: 13% w.b. (a), 16% w.b. (b), and 18% w.b. (c).

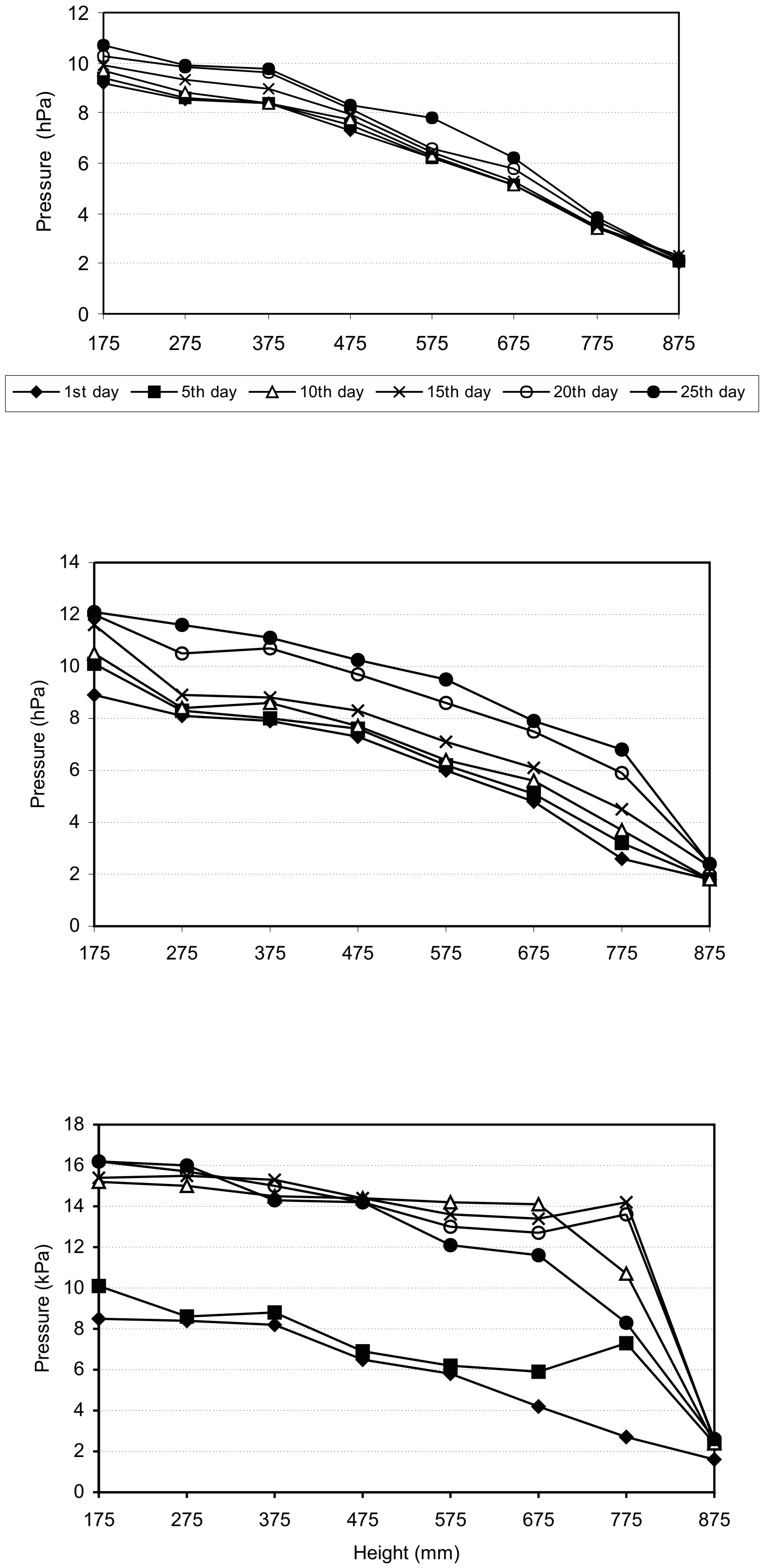

Fig. 3. Pressure values for triticale grain with moisture content: 13% w.b. (a), 16% w.b. (b), and 18% w.b. (c).

pressure were observed in the case of triticale grain with a moisture content of 13% w.b. When the silo was filled, the wall pressure in the lower part of the silo was 9.18 hPa, and at the highest measurement level it was 2.06 hPa. After 25 days of storage those values increased to 10.7 and 2.2 hPa, respectively. The initial wall pressure of the triticale grain with 16% w.b. moisture content was 8.9 hPa at the bottom and 1.8 hPa at the top. The lower pressure values when compared to those for triticale grain with 13% w.b. moisture were due to the lower bulk density. In the course of the storage period, pressure values grew gradually to reach their maximum, at the final stage of storage (12.1 hPa at the bottom and 2.4 hPa at the top). The highest pressure increase was observed from the bottom of the silo up to a height of 775 mm. At a height of 885 mm, the increase in wall pressure was only slight.

The highest increase in wall pressure values was observed in the case of the triticale grain with a 18% w.b. moisture content. On the first day of storage the pressure was 8.5 hPa at the bottom and 1.6 hPa at the top. Over 5 days, the pressure increased only slightly, with the exception of the value recorded at a height of 775 mm, where it reached 7.3 hPa. At that time, the water accumulation increase in the material stored became apparent. Between day 5 and day 10, a rapid increase in pressure values was observed, up to the value of 15.2 hPa at the bottom of the silo. Extension of storage time beyond day 10 up to day 25 caused very little increase in terms of wall pressure in the lower part of the silo, up to 475 mm, and a decrease in pressure above that level, which is consistent with grain mildewing.

CONCLUSIONS

1. The initial moisture content of triticale grain affects the temperature of grain in storage and the pressure exerted by the grain on the silo wall.

2. The highest temperatures occur in the case of triticale with an 18% w.b. initial moisture content after 25 days of storage in the upper part of the silo, and the lowest for triticale grain with a 13% w.b. moisture content.

3. In the case of triticale grain with moisture content levels of 13 and 16% w.b. the increase in pressure is uniform. The higher initial moisture content causes a stronger pressure increase in the course of storage.

4. In the case of triticale grain with an 18% w.b. moisture content, wall pressure values increase until day 10 of storage, following which the pressure decreases above the height of 475 mm due to the grain going bad.

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