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AN INFLUENCE OF OUTER ENERGY ON MOISTURE CONTENT DISTRIBUTION IN RYE GRAINS STORED IN A MODEL SILO

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Summary. Results of water content measurements in rye grains stored in a silo at variable outer temperatures are presented in the paper. The values fluctuated due to the process of cereal respiration as well as diffusion. The highest increase of the tested parameter was observed in the grain with 0.250 kg·(kg d.b.)$^{-1}$ of the water content and stored at the highest temperature. Applying the multiply regression analysis, water content was expressed as a function of its initial amounts, outer temperature, storage time and measurement point placement.

Key words: grain storage, silo, water contents, outer temperature,

INTRODUCTION

Cereal grains is stored in a dry, medium dry, wet or moistened state. The storage time depends on moisture content in the grain and its temperature [Roberts 1972]. It is prolonged during storage under dry and cool conditions. However, this can sometimes bring about some adverse processes such as kernel injuries, sprouting, impurities, mould growth, self-heating, pest development and excessive respiration [Jankowski 1958]. The respiration leads to emissions of large quantities of heat and water. If these products are not disposed with in due time, grain becomes remoistened, which causes a further increase of respiration intensity.

Water diffusion within grain mass is a result of grain's local self-heating and a storage of cereals with various moisture contents. Cereals are hygroscopic substances that absorb water to achieve balance. A potential factor difference, which for grain is a function of moisture content, temperature and pressure [Jankowski 1958, Lykov 1974] is a driving force, that is not always easy to calculate.

A precise prediction of moisture contents and the temperature of stored grain is necessary for the ventilation control [Grzesiuk and Górecki 1994]. Free water migration depends on several factors: type and quality of stored grain, size and shape of grain, temperature, initial moisture content, weather conditions, duration as well as sorption and diffusion properties. These elements make the water migration process unstable. Water moves from warmer to cooler portions of the grain. It occurs faster in grain with higher moisture content than in dry grains. Water diffusion is present in all seed types, it lasts till the end of the storage period, and water is accumulated in upper layers of the stored material [Holman and Carter 1952, Lohnes 1983, Gough *et al.* 1987, Hellevang and Hirning 1988]. A strong effect of water migration in the upper part of a silo during the storage of unpolished rice grains, due to high temperatures and high initial moisture content, was confirmed by Freer *et al.* [1990]. In that part of a silo, material was more vulnerable to spoilage and showed elevated microbial activity. Kusińska [2002] observed the same tendencies testing wheat grains.

Gough *et al*. [1987], when analyzing the temperature and moisture content in rice grains in silos with thermally isolated and not isolated walls, as well as in the silos where the grain was ventilated, found that water condensed on the silo's ceiling regardless of the wall isolation. Water migrated within the silo also depending on the insulation level. The highest moisture content in rice grains was recorded on the northern side.

Alagusundaram *et al.* [1990] and Khankari *et al.* [1992, 1994, 1995] studied the water migration within maize grain and they found that it was limited to the area near silo walls during the initial storage period, and then the changes occurred in radial and vertical directions. It was observed in silos of different sizes and it began earlier in smaller silos.

The largest number of experimental and theoretical studies was carried out using maize, rice, wheat, soybean and bean grains. There are no data available on water migration in rye grains. Therefore, the aim of the undertaken studies is to determine the influence of outer temperature on water content distribution within rye grains during its storage.

MATERIAL AND METHODS

The purchased rye grain was characterized by diverse moisture content in particular unit packages. The moisture content ranged from 0.113 to 0.136 kg·(kg d.b.)$^{-1}$. Before the experiment began, 250 kg of grain was poured out on a canvas sheet made, thoroughly mixed using shovel then it was poured into plastic barrels with a hermetic cover and stored for a day. After that, the grain was poured out again and twenty samples were taken randomly for moisture content determination. The necessary water weight that should be added to the grain in order to achieve the required moisture content was calculated on the basis of water balance after a mean moisture content determination.

The grain was moisturized using distilled water by means of spraying, then mixed and poured into barrels that were hermetically sealed with covers. The barrels were half-filled to facilitate the grain's mixing during turning. The 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 moisture content. The principle to maintain 15°C of grain was kept during all these procedures. Therefore, the grain was moisturized till the material with the required moisture content was achieved. The experimental material prepared in the above way was applied for the stand measurements.

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

The scheme of the measurement stand is presented in Fig. 1.

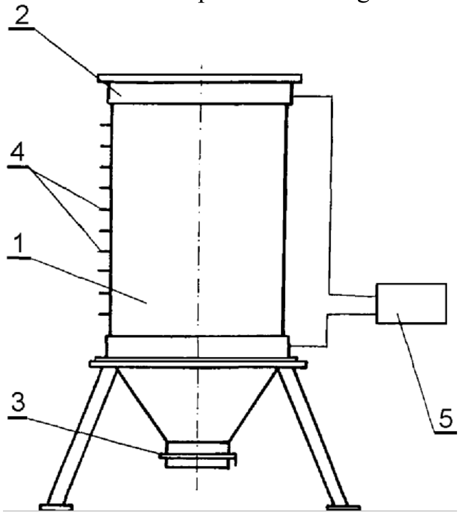


Fig. 1. A schematic diagram of the test station: 1 – silo, 2 – cover, 3 – shutter, 4 – holes, 5 – thermostat

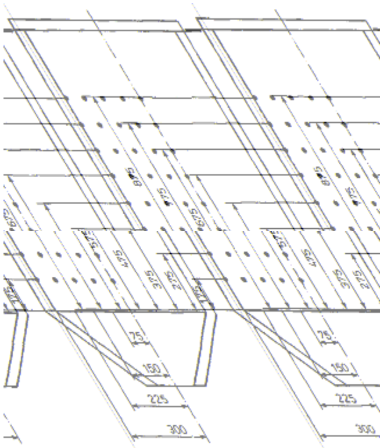


Fig. 2. The arrangement of measurement points in the silo

Its general element is a silo consisting of a cylindrical part (1) of 600 mm inner diameter and 1200 mm height, conical part with shutter (3) and cover (2) with isolation material (foamed polystyrene) lining. Cylindrical and conical parts are equipped with a thermostatic jacket, to which water of constant temperature is delivered from ultra-thermostat (5). In the cylindrical part, along the generatrix, there are holes (4) at the following distances from the cylinder edge: 175, 275, 375, 475, 575, 675, 775 and 875 mm. There were holes for moisture content measurements at five distances from the reservoir's symmetry axe (0, 75, 150, 225 and 300 mm). The scheme of measurement points distribution is presented in Fig. 2. Before the study began, the silo's cleanness, the efficiency of controlling and measuring device had to be checked and the proper water temperature in a thermostatic jacket had to be adjusted. Then the silo was filled with the prepared material up to 1050 mm height, hermetically shut with the cover and the experiment lasting 21 days began. The grain moisture content 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_o: 0.136, 0.190 and 0.250 kg·(kg d.b.)$^{-1}$. Water temperature in the thermostatic jacket was maintained at the constant level: 15, 20 and 25°C. Measurements were made in three replications.

RESULTS

During the storage of grain with 0.136 kg·(kg d.b.)$^{-1}$ of the initial water content and applying 15°C of outer temperature, no changes of moisture content during the first eight days were observed, which is presented in Fig. 3.

Beginning from the ninth day, slight biological processes were recorded, which was proved by an increase of the mean moisture content to 0.1361 kg·(kg d.b.)$^{-1}$. Within the subsequent days, the mean moisture content in the silo slightly increased, reaching the value of 0.136 kg·(kg d.b.)$^{-1}$ at the last experimental day.

A higher initial moisture content caused more changes of mean moisture content during the storage. After filling the silo with the grain with 0.190 kg·(kg d.b.)$^{-1}$ of the initial moisture content, an increase of mean moisture content was observed beginning from the second day (also at 15°C). Finally, the moisture content was 0.196 kg·(kg d.b.)$^{-1}$. The moisture content increased most intensively in the grain with 0.250 kg·(kg d.b.)$^{-1}$ of the initial moisture content reaching 0.269 kg·(kg d.b.)$^{-1}$.

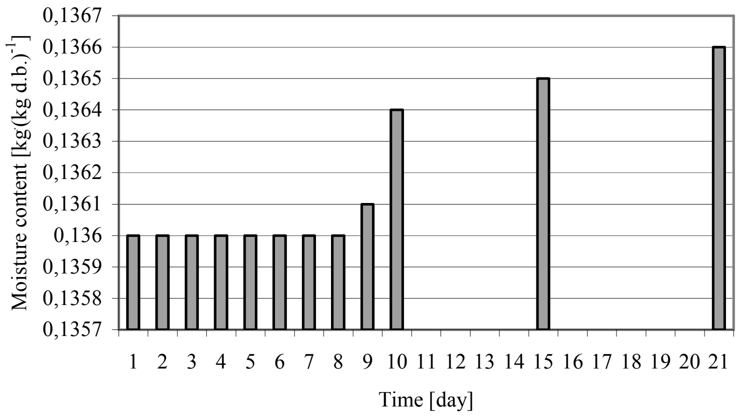


Fig. 3. An influence of the storage at 15°C of outer temperature on the moisture content in rye grains with u_o = 0.136 kg·(kg d.b.)$^{-1}$

The mean moisture content in the silo increased along with an increase of outer temperature. As a result of the grains storage with u_o = 0.136 kg·(kg d.b.)$^{-1}$ at 20°C, the mean moisture content increased to 0.137 kg·(kg d.b.)$^{-1}$; the storage at 25°C caused an increase of the mean moisture content up to 0.140 kg·(kg d.b.)$^{-1}$. A much greater increase of the moisture content was recorded during the storage of grains with higher moisture contents. Figures 4 and 5 present the mean moisture contents in rye grains with 0.196 kg·(kg d.b.)$^{-1}$ and 0.250 kg·(kg d.b.)$^{-1}$ of the initial moisture contents and stored at 25°C of outer temperature. In those cases, the mean moisture contents were 0.2045 kg·(kg d.b.)$^{-1}$ and 0.2795 kg·(kg d.b.)$^{-1}$, respectively.

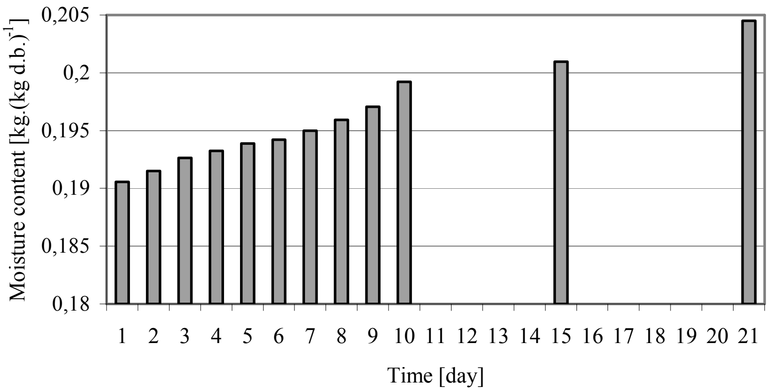


Fig. 4. An influence of the storage at 25°C of outer temperature on the moisture content in rye grains with u_o = 0.190 kg·(kg d.b.)$^{-1}$

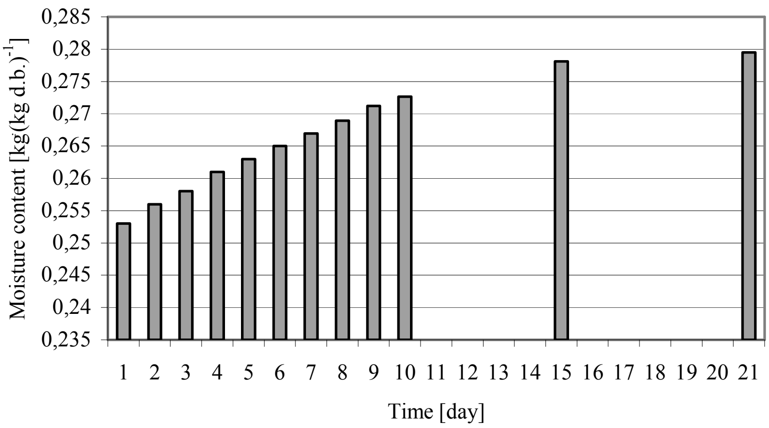


Fig. 5. An influence of the storage at 25°C of outer temperature on the moisture content in rye grains with u_o = 0.250 kg·(kg d.b.)$^{-1}$

Figures 6, 7 and 8 present the moisture content distributions in the silo's cross-section at the 21st day of grain storage with the accepted initial moisture contents at 15°C and 25°C of the outer temperature. The most uniform water distribution occurred during the storage of grains with 0.136 kg·(kg d.b.)$^{-1}$ of the initial moisture content (Fig. 6a). Inside the silo, moisture content after 21 days was 0.137 kg·(kg d.b.)$^{-1}$ in the majority of measurement points, and 0.136 kg·(kg d.b.)$^{-1}$ near the walls in the upper and lower silo's parts. The moisture content of 0.138 kg·(kg d.b.)$^{-1}$ was recorded in a small area around the silo's axis at the level of 375-475 mm.

At a higher initial moisture contents (0.190 and 0.250 kg·(kg d.b.)$^{-1}$, the moisture content increased more, but the value was lower near the walls than in the layers situated close to the axis. After the storage of grains with 0.190 kg·(kg d.b.)$^{-1}$ of the initial moisture content (Fig. 7a), the moisture content in the central part of the silo (275-775 mm level), reached up to 0.198 kg·(kg d.b.)$^{-1}$. The storage of the grain with 0.250 kg·(kg d.b.)$^{-1}$ of the initial moisture content (Fig. 8a) caused 0.276 kg·(kg d.b.)$^{-1}$ of the moisture content in the central silo's part at 475-875 mm level, and from 0.268 kg·(kg d.b.)$^{-1}$ near the walls at 475-775 mm level up to 0.262 kg·(kg d.b.)$^{-1}$ in the upper and lower parts.

In all the cases, water did not distribute uniformly. After the storage of grain at 15°C, the moisture content achieved lower values in areas close to the silo's walls. The highest moisture contents occurred in the middle of the silo. Also, greater water migration in the upper direction along with an increase of the initial moisture content was observed.

a) b)

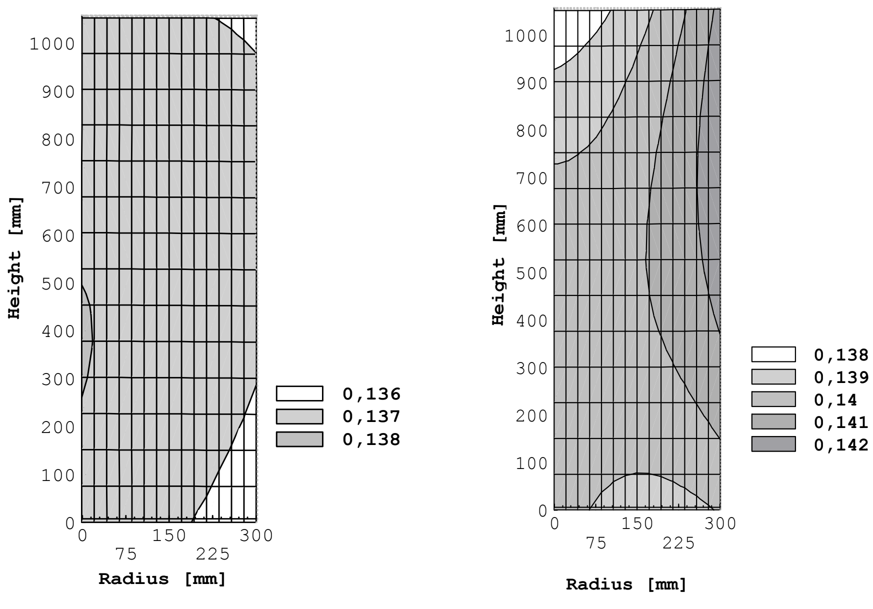
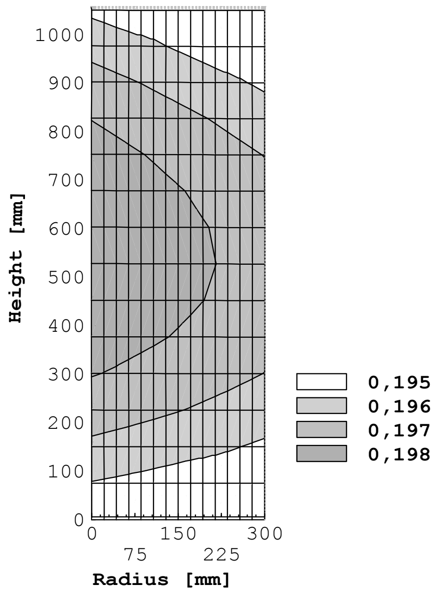


Fig. 6. Distribution of moisture content in rye grains with u_o = 0.136 kg·(kg d.b.)$^{-1}$ on the 21st day of storage at outer temperatures: a) 15°C, b) 25°C

a)



b)

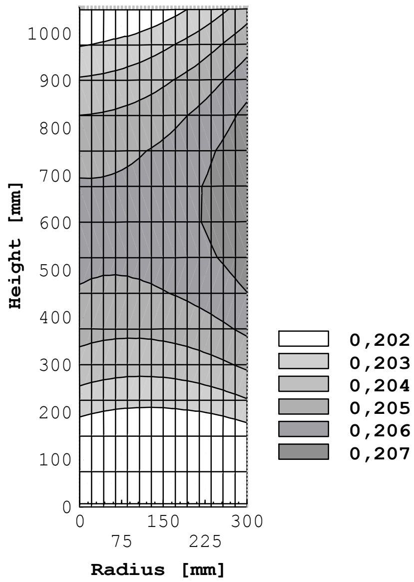
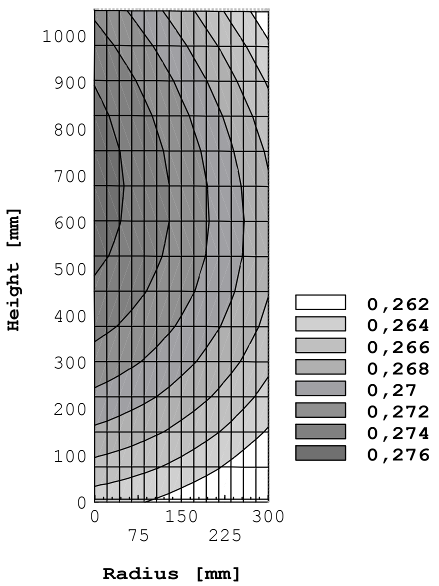


Fig. 7. Distribution of moisture content in rye grains with $u_o = 0.190$ kg·(kg d.b.)$^{-1}$ on the 21st day of storage at outer temperatures: a) 15°C, b) 25°C

a)



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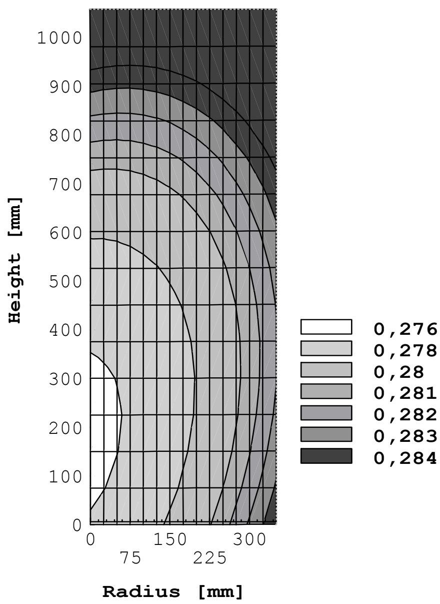

Fig. 8. Distribution of moisture content in rye grains with $u_o = 0.136$ kg·(kg d.b.)$^{-1}$ on the 21st day of storage at outer temperatures: a) 15°C, b) 25°C

An increase of the outer temperature of the silo with the cereal with 0.136 kg·(kg d.b.)$^{-1}$ of the initial moisture content to 20°C, remaining the initial temperature of loose grains at the level of 15°C, did not cause any changes of the moisture content within four days, as opposite to the process occurring at 15°C of outer temperature. Beginning from the fifth day of the experiment, an increase of the moisture content at the layer adjacent to the silo's wall was observed. On the 21st day, the moisture content near the silo's wall was 0.138-0.140 kg·(kg d.b.)$^{-1}$. The moisture contents at the points situated on the silo's axis amounted to 0.137-0.138 kg·(kg d.b.)$^{-1}$.

An increase of the moisture content near the silo's wall up to 0.202 and 0.284 kg·(kg d.b.)$^{-1}$, respectively, as well as on the silo's axis to 0.201 and 0.280 kg·(kg d.b.)$^{-1}$, respectively, due to the storage of grains with 0.190 and 0.250 kg·(kg d.b.)$^{-1}$ of an initial moisture content at 20°C, was recorded.

Experiments carried out at 25°C of outer temperature using grains with 0.136 kg·(kg d.b.)$^{-1}$ of the moisture content revealed an increase of the water content at the silo's walls by 0.001 kg·(kg d.b.)$^{-1}$ after three days. On the 21st day, the moisture content near the walls at the level above 375 mm was 0.142 kg·(kg d.b.)$^{-1}$, and on the axis from the bottom up to 775 mm – 0.140 kg·(kg d.b.)$^{-1}$ (Fig. 6b).

A higher increase of moisture content due to outer temperature was found in the grain with 0.190 and 0.250 kg·(kg d.b.)$^{-1}$ of the initial moisture contents. It caused a more intensive grain's respiration and faster water emission.

The moisture content distribution in the silo's vertical intersection after 21 days of rye grain storage with 0.190 and 0.250 kg·(kg d.b.)$^{-1}$ of the initial moisture contents and subjected to 25°C of the outer temperature is presented in Figures 7b and 8b. The manner of water distribution strictly depended on the initial moisture content. Grains with 0.136 kg·(kg d.b.)$^{-1}$ of the initial moisture content showed the tendency to accumulate water near the silo's walls. The initial moisture content of 0.190 kg·(kg d.b.)$^{-1}$ in rye grains caused its more intensive accumulation at the level of 475-875 mm, and the area of its largest content widened to vertical direction and to walls. In this case, the highest moisture content was 0.207 kg·(kg d.b.)$^{-1}$, and the lowest – 0.202 kg·(kg d.b.)$^{-1}$. A very intensive water diffusion in grain with 0.250 kg·(kg d.b.)$^{-1}$ of the moisture content due to high outer temperature was observed. The lowest moisture content, as a result of 25°C influence after 21 days of storage, was 0.276 kg·(kg d.b.)$^{-1}$ and its range included the small area around the silo's axis near the bottom; the highest moisture content was 0.284 kg·(kg d.b.)$^{-1}$ in the large-range area situated in the upper part of the silo.

The symptoms of growing mould and sprouting were observed after the storage of grains with 0.190 and 0.250 kg·(kg d.b.)$^{-1}$ moisture contents.

As a result of variance analysis involving the measured moisture contents, it was found that all the applied experimental variables exerted a significant influence on its value (at $\alpha \leq 0.01$ significance level). Water content u as a function of the initial moisture content: u_o [kg·(kg d.b.)$^{-1}$], outer temperature t_z [°C], storage time τ [days], level of measurement point h [mm], and distance of the measurement point from silo's axis r [mm], were presented, using the following equation of multiple regression:

$$u = -0.026 + 0.000236 t_z + 1.113 u_o + 0.000678\tau + 0.000001h - 0.000001r \quad (1)$$

The determination coefficient in the formula is very high (0.995). It was calculated at $\alpha \leq 0.01$ significance level. The equation is first-order polynomial. Fig. 9 compares the results of experimental studies with those achieved using the above equation (1). It is worth mentioning that the equation matched the achieved results efficiently.

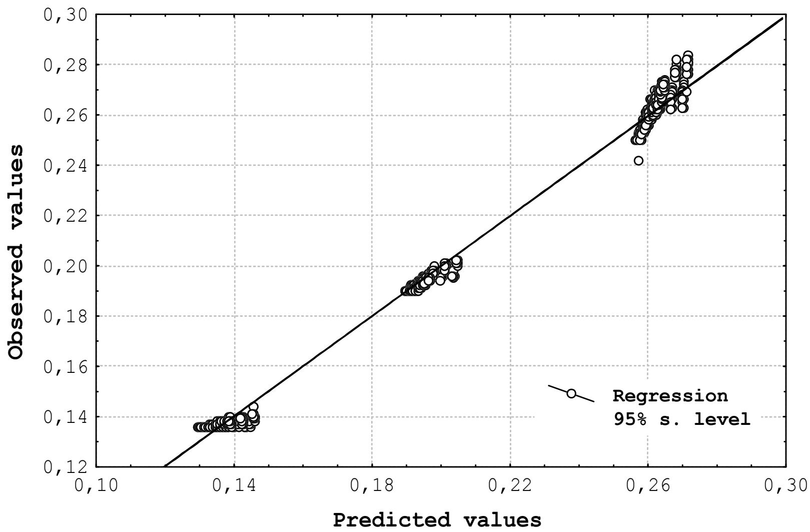

Fig. 9. Values predicted on a basis of equation (1) and experiments

The presented equation allows for the determination of the moisture content in rye grains during the storage at a random point of a silo. Its prediction makes it possible to design the ventilation process in order to maintain the grain's good quality.

The achieved results are in strict correlation with the rye temperature values that were presented in the earlier publication [Kusińska 2003]. The maximum rye temperature value corresponded to the highest water content and amounted to 46.5°C. The comparison of temperature and moisture content measurements are confirmed by the strong effects of water accumulation as a result of high temperature in the upper part of the silo observed by Holman and Carter [1952], Schmidt and Lohnes [1983], Gough *et al.* [1987], Hellevang and Hirning [1988], as well as its migration in the direction of a lower grain's temperature.

CONCLUSIONS

On the basis of the results analysis of the moisture content distribution in rye grain stored in the silo at a constant outer temperature, the following conclusions may be drawn:

1. Moisture content in rye grain significantly depends on the initial moisture content, outer temperature, storage time and the localization of a measurement point in a silo.
2. Changes of tested parameter were small, but statistically significant for grain with 0.136 kg·(kg d.b.)$^{-1}$ of initial moisture content. Higher initial moisture content and higher outer temperature caused higher increase of moisture content in grains.

3. Moisture content during grain storage at 15°C of outer temperature increased most easily in the center of the silo, then it gradually spread in the horizontal and vertical directions.

4. An increase of outer temperature, in all cases, caused an increase of moisture content near the silo's walls in the first days of storage, then an increase of moisture content in the other points of the silo with its migration, mainly in the upper direction. The moisture content increased much faster in the whole silo in case of its higher initial content. The highest moisture contents were found in the upper part of the silo (0.284 kg·(kg d.b.)$^{-1}$) after the storage of rye with 0.250 kg·(kg d.b.)$^{-1}$ of the moisture content and at 25°C.

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