

INFLUENCE OF HYDROTHERMAL PROCESSES ON FINAL MOISTURE CONTENT OF BARLEY GRAIN

Marian Panasiewicz

Department of Food Engineering and Machinery, Agricultural University of Lublin

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The paper proves a strong correlation between the range of parameters of hydrothermal treatment of barley grain (temperature of moistening, steam pressure, time of moistening) on the moisture content of grain. The study is based on a multidirectional scheme and permits conducting analysis of the influence of hydrothermal treatment on the physical properties of barley grain, mainly on its moisture content. The results obtained enabled elaborating a scheme of calculating changes in the geometrical center of grain after its steam moistening. It explains a complicated mechanism of changes in the geometrical properties of moistened grain and their effect on the bulky array. It is very important in the proper processing and preparation of grain. The achieved results and their analysis demonstrated practical directions and possibilities of hydrothermal treatment of barley grain before processing.

INTRODUCTION

Hydro and hydrothermal processes constitute a considerable part of technological operations during raw cereals processing, which involve cereal and other plant grains. In that case, the process is referred to as conditioning. The process consists of many operations associated among others with moisturizing with water or steam, seasoning, heating, and cooling of granular materials. Various methods of hydrothermal processing are significantly important during groats, flakes, and cereal snacks production. All those procedures greatly affect both the course and efficiency of processing, and evoke a spectrum of changes in physical properties of raw materials processed. As an effect, both factors determine the amount and consumption quality of cereal final products or semi-products [Gennadios & Weller, 1994; Holtz *et al.*, 2001; Jones *et al.*, 2000]. Application of these processes for any cereal material under strictly determined conditions allows for achieving its favorable changes in physical properties, namely during significant stages of the process. Structural and mechanical properties, whose properly directed change due to thermal processing is one of the principle tasks at preparing the grains for processing, can be more important. It refers in particular to grain for milling, de-hulling, flake making, or recently popular methods of cereal and seeds preparation. Treating the processed material with high-temperature and high-pressure steam leads to considerable (forced) elevation of its moisture content and temperature by a given increment, usually different for various materials [Keyser *et al.*, 1991; Singh *et al.*, 1997]. Therefore, besides expected benefits, threats resulting from improperly performed hydrothermal

process should be taken into account, because instead of improving, it may cause deterioration of the technological properties of raw material, and even its disqualification for further processing. Application of a given hydrothermal method and selection of its technological parameters (namely the range and sequence of stages) are often the most protected secret of all reckoned firms that are involved in cereal processing. It may result among others from the fact that they are complex processes, in which the influences and scope of particular factors is of complicated nature.

Influence of hydrothermal processing on selected physical properties and technological value of cereal raw materials

Cereal raw materials and foodstuff, when covering the distance from a producer to a consumer, are subjected to various operations, processes, transport, and preserving applying different means and techniques. A detailed knowledge on many physical properties of biological-origin raw materials processed is extremely important, because it guarantees an optimum selection of conditions and parameters for processing along with high quality of final products and foodstuff [Sokhansanj & Weiguo, 1996; Yamsaengsung & Moreira, 2002a, b]. Oats, like other grain or seed species, show physical properties that are typical of granular and loose materials, *e.g.* they have given shape and dimensions, volume weight, sorption properties, heat conductance ability, compactness and porosity, looseness, ability to get self-sorted, *etc.* The above traits, as a group of physical properties, are characterised by a large number of parameters associated with the structure and chemical composition of particular granular

materials as well as their behaviour due to various factors and outer conditions [Panasiwicz, 2000; Zang *et al.*, 1998; Webster, 1986]. All physical properties, systematized and combined into specific groups and sub-groups, have a positive or negative influence on processing, therefore they have to be taken into account at setting up all technological processes, at both preparatory and main stages. Even during the simplest technological operations (interaction with machine's working elements, moisture content changes, temperature oscillations, storage conditions change, *etc.*), physical properties are subjected to numerous, directed, and forced changes that result from technological line requirements. Hulasare *et al.* [1999], Zang *et al.* [1998] and Becker [1960] claim that all physical properties of cereal grains and seeds can be combined into specific groups that are closely associated to one another making a complex chemical and structural composition of particular raw materials. Bulk cereal kernels are specific isotropic material. Hydrothermal processing is one of the operations that have a considerable influence on changes in physical properties of granular materials. Its application significantly affects the range and character of changes in the internal structure of raw material processed, and the final effects greatly depend on grain's shape and other geometric traits. Muthukumarappan & Gunasekaran [1990, 1992] conducted a spectrum of studies upon changes in the size and other physical properties of grains during moisturizing and drying processes. The studies were related to sorption properties of two maize varieties moisturized under different relative air humidity levels (75, 85, 95%), as well as at different temperature ranges (25, 30, 35, and 40%). Values of heat diffusion coefficient on a base of Fick's law and changes of selected geometrical traits were determined. It was found that a steam diffusion coefficient increased along with air temperature increase and decreased when the relative air humidity increased. Volume and dimensions of grain changed in a linear mode as a result of moisturizing [Peleg, 1993]. In other studies of the above authors, a comparison of different-dimensions and shape wheat grain along with the evaluation of its behavior during cold and hot conditioning was presented. It was revealed that depending on grain size, the ratio of grain volume V_z to its outer surface area F_z (V_z/F_z) differed: it was 0.32-0.42 for fine wheat grains, and 0.50-0.55 for large grains. In the opinion of the authors, surface of fine grain is more developed than that of large grain (by 50%, on average), thus fine grains can quickly absorb water or steam and more sensitively react towards higher ranges of hydrothermal processing parameters, which is manifested as faster self-warming and transfer of heat by single grains. It requires the setting up of different (milder) conditions and parameters for hydrothermal processing [Muthukumarappan *et al.*, 1992; Peleg, 1993; Mallema, 2003]. Similar phenomena and reactions related to hydrothermal processes can also be observed in the case of final cereal products such as flakes or groats [Ekholm *et al.*, 2000; Jones *et al.*, 2000; Gennadios, 1994]. Amongst a variety of physical properties that change during hydrothermal processes and affect the grain's and seed's durability, there are structural and mechanical features [Fredlund *et al.*, 1997]. As the authors state, processes of grain or seed (namely dry ones) intensive moisturizing lead to a sudden increase of tensions

that can evoke numerous damages including characteristic cracks of endosperm. Considering the strength features of single cereal grains or seeds, terms applied in physics to describe classical solid's properties such as brittleness, plasticity, and elasticity were used [Nuebel & Peleg, 1993]. These traits correspond to some model behavior of solids due to outer forces. However, no-one can completely characterize the strength properties of organic material on the basis of methods applied for crystalline structure materials because of irregular and very diversified cellular structure of granular products [Abu-Ghannam & McKenna, 1997]. In addition, strength properties of grains and seeds strongly depend on their initial moisture content and its changes during hydrothermal and thermal processes [Hulasare *et al.*, 1999]. At low moisture content, cereal grains and some seeds show properties recalling the brittle materials with slight share of elastic features. Elastic traits dominate at higher moisture content with some contribution of plastic features, and grains show only plastic properties for the highest moisture levels. However, humidity ranges, at which the surplus of a particular trait can be referred to, are different for every cereal grain or seed type. Influence (increase) of moisture and heat on granular materials makes their deformation process longer that precedes their breaking. At the same time, their brittleness decreases and absolute deformation increases, which partially prolongs the time of final breaking and damage of grains or seeds [Mallema, 2003]. The study indicates the diversity of the strength traits occurring within the same plant species. At the same moisture content, these differences may reached even up to 50%, which results from the fact that the durability of a fine grain may be by 30-60% higher than that of the large one. Differences of strength features are also present among anatomical parts of grain, but mechanical durability of fruit-seed cover is 2-3-fold higher than that for de-hulled kernel. Among here presented reference reviews, most of publications and study results referred to various aspects and conditions resulting from hydrothermal processes applied to cereal grains, seeds and selected cereal products (groats, flakes). A great and multi-layer influence of hydrothermal processing on the change of chemical composition of tested raw materials as well as increase of availability of some components and chemicals was also proved in part of cited publications. Much smaller number of works was devoted to changes of physical properties that occur due to steam influence. From the cited references it results that a range of studies was reduced to perception of the facts with no attempts to elucidate the reasons of some parameters interaction (mainly temperature and steam pressure) with processed grains or seeds. Most of the cited studies referring to hydrothermal processing were conducted according to different methods and using different raw materials (namely at groats and flakes production), which made it impossible to compare the results published. Intensity of cereal grains, leguminous and oil seeds or loose materials processing applying hydrothermal and hydrothermal-mechanical methods depends on the temperature and moisture content, the mechanical energy input, steam pressure as well as processing time. In general, there are no fundamental studies that would take into account the interactions between those parameters (Figure 1).

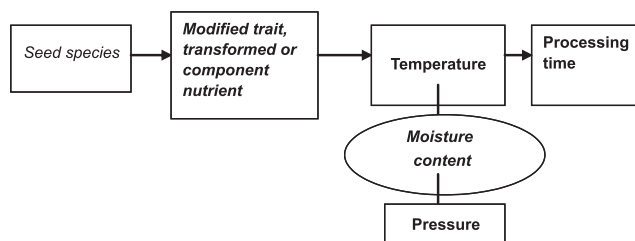


FIGURE 1. Scheme of a complex study upon hydrothermal processing in the context of interactions and correlations between particular factors.

From the reference review it follows that some experimental and theoretical directions that would enabled elucidating and elaborating correlations between physical properties of material processed and applied parameters of hydrothermal processing (moisturizing time, temperature of moisturizing agent – water, steam) or steam pressure can be distinguished.

AIM AND SCOPE OF THE STUDY

The present study was aimed at analysing the course of hydrothermal processing and evaluating changes of selected physical properties of barley grains due to varied parameters applied. Basing on preliminary study results and literature data, the following working hypothesis was formulated: Hypothesis H1. There are specific conditions and strict dependence between the range of applied parameters of hydrothermal processing (temperature of moisturizing agent, steam pressure, moisturizing time) and physical properties of raw material processed. Completion of the aim and verification of formulated hypothesis required a variety of studies including: determining and evaluating the range of grain hygroscopic properties change associated with absorption or desorption of water or steam dynamics during different hydrothermal processes. In addition, taking into account the aim and scope of the study, an attempt was undertaken to work out a mathematical model describing the hydrothermal processing of oats and interactions related to material processed. The model fundamentals were based on observations and analysis of hydrothermal operations that are commonly applied at producing groats and cereal flakes, and on the other hand, on specificity and conditions of methods offered in study aims.

MATERIALS AND METHODS

Grains of husking spring barley from control cultivation (plots) were used for experiments. Before experiments, grain was purified on sieve-pneumatic separator of NSP1 (impurity content was below 1%) and sorted (using sieve with oblong holes) onto fractions (fine, medium, and thick). Medium fraction was used for studies as the most representative and most often applied for groats and cereal flakes production. Then, grain was subjected to qualitative evaluation determining – in accordance with obligatory requirements – initial moisture content, 1000-kernel weight, loose and shaken density, slip and raising angles, as well as granulometric distribution. Subsequent study stage was related to the selection of method and parameters of hydrothermal processing along with setting

up the range of initial moisture contents for proposed conditioning methods. At every study stage, depending on the processing method, grain was moisturized by adding calculated amount of water. Oats grain was placed in hermetically closed containers and stored in a cooling chamber at 4°C ($\pm 0.5^\circ\text{C}$), which ensured the same thermal and humidity conditions for all tested samples. Such prepared and preliminarily moisturized grain was moisturized with steam under different temperatures and pressures. Ranges of selected physical properties were determined after hydrothermal processing by means of instrumental techniques; which made it possible to evaluate correlations between hydrothermal processing parameters and behavior and structural changes of raw material.

Testing stand and method for grain moisturizing with steam. Grain moisturizing with steam was realized in a designed laboratory dryer-mixer with double heating coat and connected to a steam generator (Figure 2).

The device enabled moisturizing grain under different hydrothermal conditions (variable moisturizing time, steam pressure and temperature). Single grain samples ($m=1$ kg) moisturized to the assumed initial moisture contents ($w_{pp1}=10\%$, $w_{pp2}=12\%$, $w_{pp3}=14\%$, $w_{pp4}=16\%$, $w_{pp5}=18\%$, ± 0.5), were placed in a dryer, and then steam was supplied to a desired pressure and temperature. Three steam pressure levels were set up: $p_{p1}=0.10$ MPa, (steam temp. $t_{p1}\sim 99.96^\circ\text{C}$), $p_{p2}=0.14$ MPa, (steam temp. $t_{p2}\sim 109.33^\circ\text{C}$) and $p_{p3}=0.28$ MPa, (steam temp. $t_{p3}\sim 131.20^\circ\text{C}$). Steam processing time was $\tau_{np1}=5$ min, $\tau_{np2}=10$ min, and $\tau_{np3}=15$ min.

RESULTS AND DISCUSSION

Hydrothermal processes in cereal grains and seeds processing are widely utilized in the foodstuff industry, namely groats and flake production as well as other products referred to as “breakfast snacks”. From the point of view of processing technology, as well as the amount and quality of a final product, knowledge of physical properties of processed grain and their changes during preliminary or main processes is very important. Therefore,

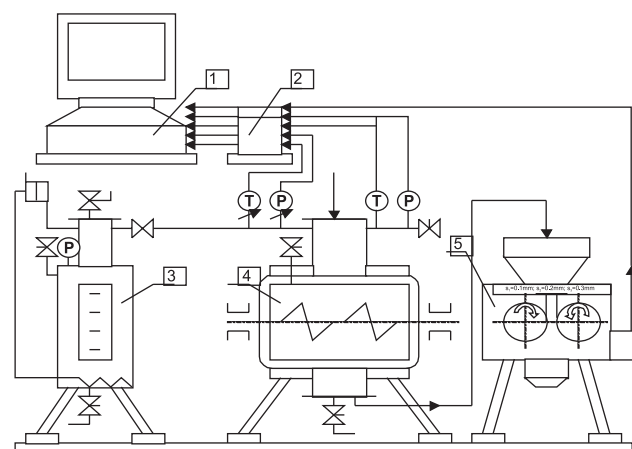


FIGURE 2. Scheme of a laboratory stand for steam pressure processing of granular products:

1 – computer, 2 – converters of physical parameters (temperature, pressure), 3 – steam generator, 4 – dryer-mixer with heating coat, 5 – crusher.

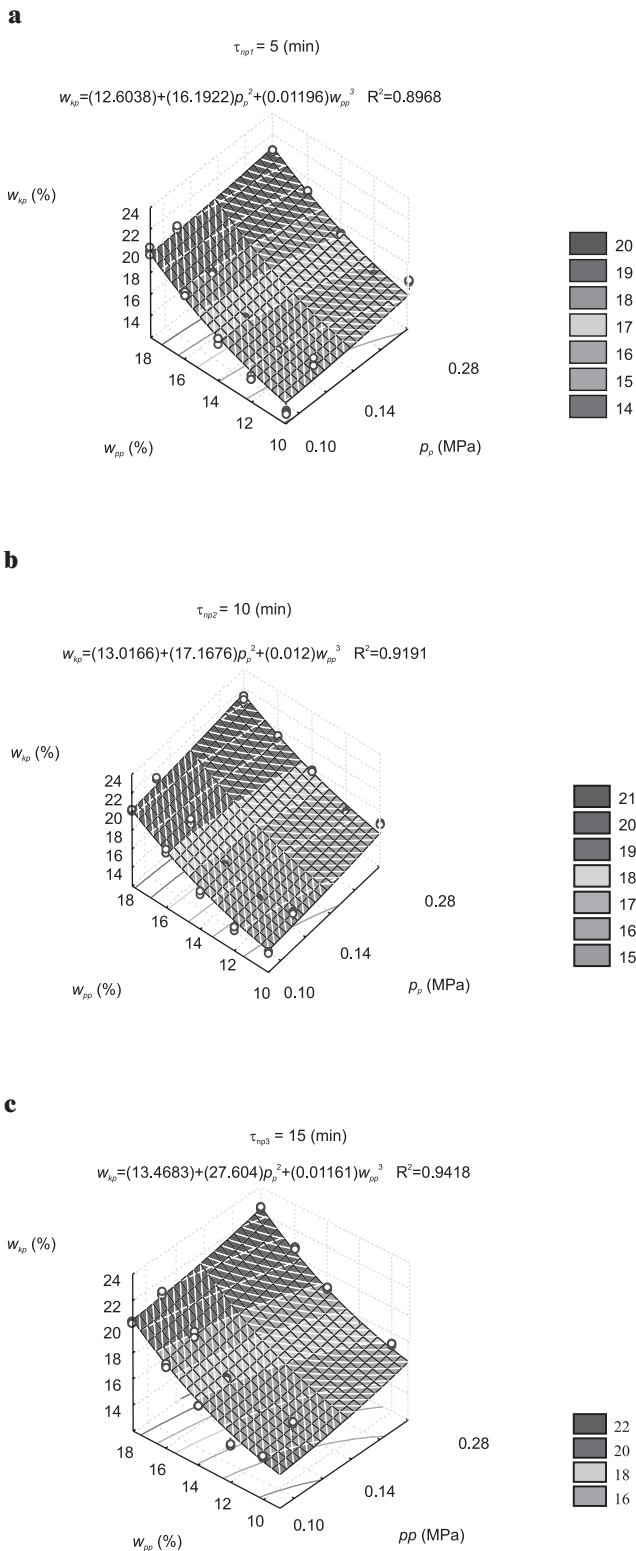


FIGURE 3. Influence of steam pressure and moisturizing time on final moisture content of barley grains: a) $\tau_{np1} = 5 \text{ min}$, b) $\tau_{np2} = 10 \text{ min}$, c) $\tau_{np3} = 15 \text{ min}$.

behavior and range of changes at naked oat grains occurring during its moisturizing with steam were evaluated, which was in accordance with the assumed aims. Analysis of the achieved results was performed taking into account different levels of initial moisture contents, different temperatures and steam pressure as

TABLE 1. Multiple regression equations describing the influence of steam pressure p_p and initial moisture content w_{pp} on changes in final moisture content w_{kp} .

Time of grain moisturizing with steam τ_{np} (min)	Final moisture content w_{kp} (%)	Determination coefficient R^2
$\tau_{np1} = 5$	$w_{kp} = (12.6038) + (16.1922)p_p^2 + (0.001196)w_{pp}^3$	$R^2 = 0.8968$
$\tau_{np2} = 10$	$w_{kp} = (13.0166) + (17.1676)p_p^2 + (0.0012)w_{pp}^3$	$R^2 = 0.9191$
$\tau_{np3} = 15$	$w_{kp} = (13.4683) + (27.604)p_p^2 + (0.001161)w_{pp}^3$	$R^2 = 0.9418$

well as moisturizing times. The results obtained showed a great influence of the applied parameters of hydrothermal processing on changes in many physical properties of oat grain, mainly referring to moisture content and strength features. A comparison of initial and final moisture contents at tested grain revealed that the former trait along with moisturizing time greatly affected the range of changes, but it was manifested mainly at longer times of the moisturizing process, *i.e.* $\tau_{np2} = 10 \text{ min}$ and $\tau_{np3} = 15 \text{ min}$. The longer time the steam affects grain, the higher its final moisture content due to prolonged steam absorption period by internal structure. Furthermore, the course and character of moisture content change (within the range of the studied moisturizing parameters) was described in a form of third-order polynomial (Figure 3) for each of three moisturizing times.

The achieved study results were subjected to statistical processing using variance analysis and confidence intervals (HSD Tukey's test). It revealed that the change of moisture content gradient for grain moisturized within three time ranges in a system of two variables (grain's initial moisture content, and steam pressure) depended on moisturizing time, and to a lesser extent on grain's initial moisture content and steam pressure (within studied ranges), (Table 1). Mean values of moisture content changes indicate that under comparable conditions of moisturizing time and steam pressure, 2-2.5-fold higher moisture content increase was recorded for grains of a low initial moisture content ($w_{pp1} = 10\%$, $w_{pp2} = 12\%$) than for those of the high one ($w_{pp4} = 16\%$ and $w_{pp5} = 18\%$). It confirms the assumed thesis that dry grain with a low initial moisture content is more vulnerable to intensive action of steam, and dynamics and amount of water absorbed are directly proportional to changing moisturizing conditions. For higher moisture contents ($w_{pp4} = 16\%$, $w_{pp5} = 18\%$), the amount of absorbed water decreases, but it refers to all moisturizing times. Applying multiple regression analysis, equations describing the influence of steam pressure and grain's initial moisture content on changes in final moisture content of grain moisturized at different time ranges, were defined. Detailed data related to statistical processing are presented in Tables 1 and 2. On the basis of results from the present experimental stage, a strict dependence can be determined between the applied parameters of steam moisturizing and – being a consequence of that – the range of final moisture content at grain processed. From the technological point of view, knowledge on the range of changes in oat grain moisture content, at given parameters of hydrothermal processing, may be useful for its further processing (flake making, or so-called *preparing*) or preparation as an additive to other

TABLE 2. Measurements of final moisture contents for grain moisturized with steam.

Parameters		Final moisture content $w_k, \%$ (mean values)	Uniform groups *
Moisturizing time $\tau_{pp1} = 5\text{min}$	Initial moisture content	10	a
	$w_{pp} (\%)$	12	a
		14	a
		16	b
	Steam pressure p_p (MPa)	18	c
0.10		a	
0.14		a	
Moisturizing time $\tau_{pp2} = 10\text{min}$	$w_{pp} (\%)$	0.28	a
		10	a
		12	a
	Steam pressure p_p (MPa)	14	b
		16	c
Moisturizing time $\tau_{pp3} = 15\text{min}$	$w_{pp} (\%)$	18	d
		0.10	a
		0.14	a
	Steam pressure p_p (MPa)	0.28	a
		10	a
Moisturizing time $\tau_{pp3} = 15\text{min}$	$w_{pp} (\%)$	12	a
		14	a
		16	a
	Steam pressure p_p (MPa)	18	b
		21.29	c
Moisturizing time $\tau_{pp3} = 15\text{min}$	$w_{pp} (\%)$	0.10	a
		0.14	a
		0.28	a
	Steam pressure p_p (MPa)	17.07	a
		17.86	ab
Moisturizing time $\tau_{pp3} = 15\text{min}$	$w_{pp} (\%)$	19.16	b
		17.51	a
		15.70	a
	Steam pressure p_p (MPa)	16.30	a
		18.00	a

*the same letter stands for the lack of significant difference between mean values within a given group at a significance level of $\alpha=0.05$

food products. Furthermore, moisture content, as one of the main physical traits, greatly affects the changes of other group of grain's physical properties, including structural and mechanical features. During the processing (e.g. breaking, flaking, etc.), continuous changes and modifications of moisture content levels are necessary as they affect a change in grain's resistance to crushing.

Comparing presented results of study to another researchers [Abu-Ghannam *et al.* 1997; Ekholm *et al.*, 2000; Becker, 1960; Keyser *et al.*, 1991], I have to ascertain that character, dynamics and study scope of changes in moisture content of variety grains were similar. Theses of Peleg [1993], Sinh *et al.* [1997], and Sokhansanj *et al.* [1996], are confirmed by the achieved study results. Intensity of cereal grains, leguminous and oil seeds or loose materials processing applying hydrothermal and hydrothermal-mechanical methods depends on the temperature and moisture content, the mechanical energy input, steam pressure as well as processing time. Most of studies [Muthukumarappan *et al.*, 1992; Keyser *et al.*, 1991; Hualsare *et al.*, 1999], which are carried on at the moment referring to hydrothermal processing were conducted according to different methods and using different raw materials (namely at groats and flakes production), which made it impossible to compare the results published.

Calculations of geometrical center change at grains subjected to hydrothermal processing

The direction (orientation) of de-hulled kernel or seed during processing depends on many physico-mechanical traits. As study results revealed, more or less intensive hydrothermal operations upon oat grains led to changes in geometric traits, namely linear dimensions (length, width, thickness) as well as spatial ones

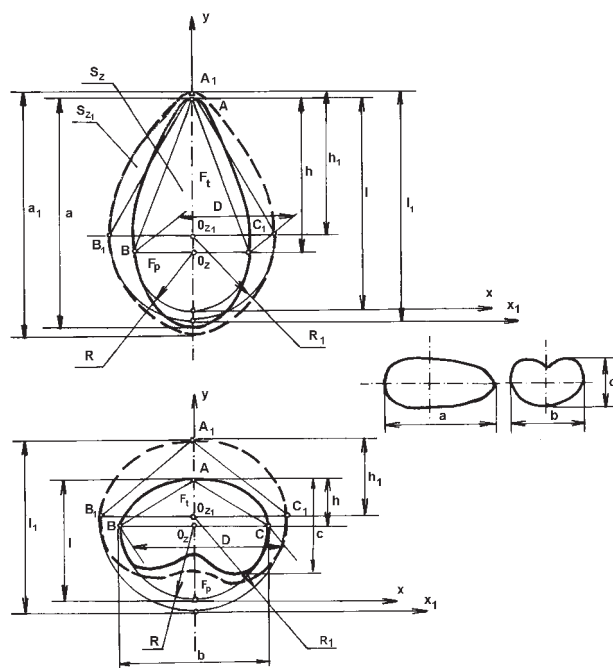


FIGURE 4. Scheme to determine the oat's grain geometrical center: O_z, O_{z1} – geometrical center of grain before and after steam moisturizing, S_2, S_{21} – surface area of grains before and after hydrothermal processing; a – kernel's length (longest dimension), b – grain's width (mean dimension), c – grain's thickness (smallest dimension).

(surface area, volume, shape coefficient). A spatial re-orientation of geometrical center of moisturized grains is a consequence of those parameters change, which may influence their behavior in many processes, e.g. de-hulling or flaking. Formation of symmetrical objects is one of generalized rules, according to which the biological formation of grains and seeds takes place, which may be used to determine its geometrical center (Figure 4).

Symmetry axis divides grain into two the same or very similar (in relation to the weight and dimensions) halves. Assuming some geometrical similarity, both halves of grain or seed divided by symmetry axis may be considered as second-order complex planes. To determine the geometrical center of a grain, theoretical mechanics rules can be involved. In accordance to it, two uniform grain's parts formed as a result of making the symmetry axis, have geometry center that lies onto that axis. Accepting a simplification that barley grain in its transverse section is a geometrical figure that consists of a triangle and semicircle, geometrical center for those planes can be easily determined. Having the geometrical dependences (Figure 4), the following formula that allows for calculating the grain's geometrical center can be helpful:

$$O_z = \frac{F_t Y_t + F_p Y_p}{F_t + F_p} \tag{1}$$

where: O_z – grain's geometrical center; $F_t = Rh$ – surface area

for triangle ABC (m^2); $R = \frac{D}{2}$ – circle radius (m); D – larg-

est (clone to natural grain's curvature) diameter (m); $Y_t = \frac{h}{3}$

– coordinates of triangle's geometrical center (m); $F_p = \frac{\pi R^2}{2}$

– circle's surface area (m²); $Y_p = \frac{4R}{3\pi}$ – coordinates for semi-circle's geometrical center (m).

Putting data to equation (1) and transforming it, we achieve:

$$O_z = \frac{2(h^2 + 2R^2)}{3(2h + \pi R)} \quad (2)$$

Analogously, the change of geometrical center localization of a grain after its moisturizing can be determined:

$$O_{z'} = \frac{2(h_1^2 + 2R_1^2)}{3(2h_1 + \pi R_1)} \quad (3)$$

Equations (2) and (3) allow for theoretical determination of oat grain's geometrical center. As it was underlined, any change of grain's physical properties (quantities l and D in particular) leads to the change of geometrical center localization from O_z to $O_{z'}$, which in turn may lead to new spatial re-orientation of an object. Below drawn conclusions indicated the complex and multi-factor character of steam influence on processed barley grain.

CONCLUSIONS

1. Different parameters of hydrothermal processing (more the time of direct steam moisturizing than steam pressure) affect both grain's hygroscopic properties.

2. A strict dependence between moisture content increase and steam moisturizing time was found: the longer the moisturizing time, the higher the level of final moisture content. Grain with low moisture contents ($w_{pp} = 10\%$ and 12%) was characterised by higher ability and dynamics to water absorption than that of moisture contents $w_{pp} = 16\%$ and 18% . Those differences (for different samples and study stages) oscillated within 30-60% range.

3. Particular dependencies and change ranges of selected physical properties of barley's grain due to steam influence enabled evaluating their practical application (further flaking, thermal processing or *preparing*).

4. On the basis of up-to-date knowledge, the achieved study results, and observations, an attempt was undertaken to elaborate the rules for calculating a change in grain's geometrical center position after intensive moisturizing. It made a complex mechanism of physical properties changes in barley's grain more understandable, both during its preparing and processing.

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WPLYW ZABIEGÓW HYDROTERMICZNYCH NA WILGOTNOŚĆ KOŃCOWĄ ZIARNA JĘCZMIENIA*Marian Panasiewicz**Katedra Inżynierii i Maszyn Spożywczych, Akademia Rolnicza w Lublinie*

W pracy wykazano, iż istnieją określone uwarunkowania i ścisła zależność pomiędzy zakresem zastosowanych parametrów obróbki hydrotermicznej ziarna jęczmienia (temperatura czynnika nawilżającego, panujące ciśnienie pary wodnej, czas nawilżania), a zmianą jego wilgotności. Zakres pracy obejmował wielokierunkowy układ badań, który pozwolił na przeprowadzenie analizy wpływu zabiegów hydrotermicznych na zmianę wybranych cech fizycznych ziarna jęczmienia—głównie wilgotności. W oparciu o wyniki badań i spostrzeżenia opracowano zasady obliczania zmiany położenia geometrycznego środka przestrzeni ziarna po intensywnym nawilżaniu parą wodną. Przybliżyło to złożony mechanizm zmian cech geometrycznych nawilżonego ziarna i ich wpływ na zmianę jego orientacji przestrzennej, ważną w procesach jego przygotowania i właściwego przerobu. Uzyskane wyniki badań i ich analiza wskazały praktyczne kierunki i możliwości wykorzystania procesów obróbki hydrotermicznej ziarna jęczmienia przed przerobem.