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Moisture-induced changes of mass and dimension characteristics in some cereal grains**

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A b s t r a c t. The seeds of barley, oat, rye, and two varieties of wheat were studied during wetting thereof with special respect to changes in their mass and dimensions. Two levels of wetting were used: 6-h wetting close to the end of imbibition, and 24-h wetting close to the start of germination. The results of these experiments show that the measured quantities can be well described by the Gaussian distribution. Gaussian distribution is applied for description of the wetting effects that can be well approximated also by a second-degree polynomial of the initial state. Even though an increase in the mass, length, width, and thickness was the main effect of wetting, opposite trends in some dimensionally dependent cases were also observed. Drying of the wetted specimens led to a state that differed only slightly (less than 1%) from the initial state. Among the dimensional characteristics, the highest changes were observed in the grain length.

K e y w o r d s: cereal grains, dimension, mass, water, swelling, shrinkage

INTRODUCTION

Movement of water into ripe and dry grains is, on the one hand, a critical step in germination and, on the other hand, a critical step of dampening, an undesirable process leading to losses of both quality and quantity of the stored cereals (Harper *et al*., 1970). For seed germination, the location of seeds in moist conditions plays a crucial role (Manz *et al*., 2005; Mares 1983, 1999; McGuinness *et al*., 2000; Schopfer, 2006). This is known under the complex term 'imbibition' (Weitbrecht *et al*., 2011). During imbibition, the dimensions of the seeds change following the process of increasing moisture. Variation in the rate or the pathway of water movement may be affected by the plant species (Feyyollahzaden *et al*., 2014; Ünal *et al*., 2013) including the dormancy phenotype (Finch-Savage and Leubner-Metzger, 2006; Mares *et al*., 2005; Rathjen *et al*., 2009). Seed sorption is a driving force of the process (Blahovec and Yanniotis, 2009, 2010; Yanniotis and Blahovec, 2009), while mainly humidity, temperature, and pressure play the role of external parameters (Blahovec and Kubát, 1987). Most of the biochemical and molecular changes are intensified during the first hours of imbibition (Harb, 2012).

In germination, the imbibition process is followed by two more steps (Weitbrecht *et al*., 2011). In imbibition the seed moisture content steeply increases up to a value representing about a 50% increase of the imbibed seed mass, whereas in germination, there is a second step where the moisture increase stops and then in a third step, it continues again. The prolongation of the first step for wheat is about 5 h and does not strongly depend on the seed state dormancy (Rathjen *et al*., 2009). In this step, grain wetting is limited to the seed coleoptile and to the surface of the seed (Rathjen *et al*., 2009). The second step represents a set of metabolic processes (Schopfer and Plachy, 1984; Weitbrecht *et al*., 2011) necessary for the seed germination in the third step. The second and the third steps are very variable depending on the different species and different conditions. For different wheat cultivars of different dormancy, Rathjen *et al* (2009) reported the time of the second step of approximately 10 h (for a non-dormant variety) and *ca*. 50 h for dormant varieties. At the beginning of the third

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step, the seed moisture increases in a short time. In wheat, the process of the secondary wetting at the beginning of the third step needs only about 10 h (Rathjen *et al*., 2009). In the remaining part of the third step, no further increase of the seed moisture content was observed.

Seeds have different shapes (Dziki *et al*., 2013; Zare *et al*., 2013), therefore, shape differences, given partly by domestication thereof (Fuller, 2007), can be used for sorting them according to the type, cultivar, quality *etc*. (Dornez *et al*., 2011; Mebatsion *et al*., 2012). The seed shape was studied with computer vision (Shouche *et al*., 2001) as a basis for automatic sorting. The volume of the seeds during their germination increases and also their shape changes even in cases of very symmetric shapes close to the spherical one (Robert *et al*., 2008). The process of the moisture increase is an inhomogeneous process (Rathjen *et al*., 2009); therefore, the changes in the seed shape during wetting should be nontrivial (Waszkiewicz, 1988, Blahovec and Yanniotis, 2010); they indicate details of the processes controlling the pre-germination stage of plant growth.

In this paper, the basic dimensional characteristics of cereal grains (winter wheat, rye, barley, and spring hulless oat) were studied close to the end of imbibition (after 6 h of wilting) and in the second step of germination (after 24 h of wilting). We aimed at determination of the stimulated dimensional changes in relation to the original dimension and shape of grains and analysis on the basis of the Gaussian hypothesis.

MATERIAL AND METHODS

The grains of winter wheat (cultivars Fermi and Sultan), winter rye (cv. Kapitán), winter barley (cv. Lester), and hulless oat (*Avena nuda* L. – cv. Saul) harvested in 2012 (Experimental Station of the University of Life Sciences in Prague-Suchdol) were kept in cold, dry storage (temperature below 20°C, humidity below 50%) up to the period in which the experiments were carried out (September-November, 2013). For every tested material, three specimens were randomly selected: I (30 grains) for determination of moisture content by the gravimetric method, which is based on weighing the whole specimen prior to and after drying (4 h at 104°C, Sahin and Sumnu, 2008). Specimens II and III comprising 100 individual grains were used for the wetting experiment in distilled water at 25°C – specimen II for 6-h and specimen III for 24-h experiments.

The wetting experiments were based on measurements in each individual grain. Every grain was weighed (laboratory weight with an accuracy of 0.0001 g) to determine its mass and measured to determine its length (the longest dimension of the grain), width (the biggest dimension perpendicular to its length), and thickness (the lowest dimension perpendicular to its length) to determine the initial (I) state. The dimensions were measured manually using a caliper with an accuracy of 0.05 mm. The same measurements were repeated after wetting (W) and at the end after 4-h drying (D) of specimens II and III at 40°C. During the whole process, the identity of each grain was saved.

The results were statistically evaluated using standard means in Excel.

RESULTS AND DISCUSSION

The results obtained are represented by the mean values and the standard deviations given for the grain: mass, length, width, and thickness in Table 1. The coefficient of variation (CV) of the grain mass is less than 21% for the individual crops, whereas the CV of the dimensional characteristics is less than 11%. Every individual experimental result represents, among the other 99 ones, a one-percent increase in the cumulative distribution; hence, the cumulative distribution of the individual parameter and the individual crop was arranged as a plot of the cumulative coordinate $0.005+\frac{i-1}{100}$ versus the *i*-th parameter in the increasing set of data. The 'experimental' cumulative distributions were approximated by Gaussian cumulative distributions given by the calculated mean values and standard deviations. This is given for the mass of the barley grains in Fig. 1. This figure shows that the experimental data are well described by the Gaussian distribution. The main differences from this distribution were observed mainly at the highest values of the curves obtained in the wet state. The differences from the Gaussian approximation at the other parts of the plots in Fig.1 have a rather stochastic character and they could represent deviations from the basic Gaussian characteristic of the grain set.

We suppose that the variability of the measured parameters represents superposition of the basic product variability that could be described by the Gaussian parameters given for the individual properties (mass and dimensional characteristics) and variability caused by the measurement method and the parameter variations of the higher order. We can understand the Gauss equation as an approximation formula of the data and the deviations from it then can be described similarly as in other cases of fitting experimental data (Christopoulos and Lew, 2000). For evaluation of the fitting, we use *RMS* (root mean square) defined as:

$$RMS=\sqrt{\frac{SSE}{df}}, \qquad (1)$$

where *SSE* is the sum of squared differences between experimental values and those given by the Gaussian approximation and *df* degrees of freedom. For comparison of the measure of deviations from the Gaussian description obtained, we calculated the $\frac{RMS}{SD}$ ratio as a measure of both characteristic values *RMS* and standard deviation of the basic distribution. This ratio, calculated for the measured mass values, is given in Fig. 2. This figure shows big variability

T a b l e 1. Basic characteristics of grain: mass, length, width, thickness

Crop	State	6 h wetting			24 h wetting		
		MV	*SD*	*CV*	*MV*	*SD*	*CV*
				Grain mass			
	Initial	0.0444	0.0065	14.7	0.0472	0.0074	15.7
Barley	Wet	0.0611	0.0080	13.0	0.0712	0.0102	14.3
	Dried	0.0442	0.0065	14.7	0.0462	0.0073	15.8
	Initial	0.0244	0.0051	20.8	0.0274	0.0056	20.5
Oat	Wet	0.0321	0.0059	18.4	0.0383	0.0078	20.4
	Dried	0.0239	0.0061	25.3	0.0264	0.0055	20.9
	Initial	0.0389	0.0081	20.9	0.0377	0.0068	18.1
Rye	Wet	0.0493	0.0104	21.1	0.0564	0.0107	19.0
	Dried	0.0385	0.0081	21.0	0.0370	0.0066	18.0
	Initial	0.0503	0.0086	17.2	0.0505	0.0091	18.0
Fermi	Wet	0.0643	0.0110	17.1	0.0727	0.0124	17.1
	Dried	0.0496	0.0081	16.3	0.0493	0.0089	18.0
	Initial	0.0511	0.0084	16.5	0.0534	0.0076	14.3
Sultan	Wet	0.0646	0.0114	17.6	0.0769	0.0120	15.6
	Dried	0.0500	0.0089	17.9	0.0529	0.0074	14.0
				Grain length			
	Initial	8.32	0.79	9.5	8.38	0.90	10.7
Barley	Wet	8.35	0.72	8.6	8.78	0.88	10.1
	Dried	8.26	0.76	9.1	8.52	0.78	9.2
	Initial	6.69	0.63	9.4	6.89	0.66	9.5
Oat	Wet	7.08	0.62	8.7	7.20	0.69	9.5
	Dried	6.57	0.59	9.0	6.90	0.63	9.1
	Initial	7.53	0.79	10.5	7.40	0.72	9.8
Rye	Wet	7.79	0.75	9.7	7.66	0.78	10.2
	Dried	7.51	0.78	10.4	7.54	0.73	9.6
	Initial	6.19	0.35	5.7	6.19	0.37	6.0
Fermi	Wet	6.37	0.37	5.8	6.43	0.50	7.8
	Dried	6.17	0.37	5.9	6.32	0.34	5.3
	Initial	6.17	0.39	6.3	6.27	0.32	5.1
Sultan	Wet	6.40	0.45	7.0	6.68	0.54	8.1
	Dried	6.15	0.39	6.3	6.33	0.39	6.1

T a b l e 1. Continuation

Crop	State	6 h wetting			24 h wetting		
		MV	*SD*	*CV*	*MV*	*SD*	*CV*
				Grain width			
	Initial	3.44	0.22	6.4	3.49	0.21	6.1
Barley	Wet	3.46	0.26	7.4	3.65	0.30	8.1
	Dried	3.38	0.23	6.9	3.53	0.25	7.2
	Initial	2.50	0.21	8.2	2.63	0.22	8.5
Oat	Wet	2.53	0.23	8.9	2.59	0.26	10.2
	Dried	2.48	0.20	8.1	2.61	0.21	8.2
	Initial	2.71	0.26	9.7	2.67	0.23	8.5
Rye	Wet	2.76	0.29	10.6	2.69	0.28	10.4
	Dried	2.71	0.26	9.7	2.63	0.26	9.9
	Initial	3.68	0.29	7.8	3.63	0.33	9.2
Fermi	Wet	3.73	0.31	8.4	3.74	0.38	10.2
	Dried	3.68	0.31	8.3	3.71	0.35	9.5
	Initial	3.46	0.32	9.2	3.55	0.28	7.9
Sultan	Wet	3.57	0.33	9.1	3.79	0.32	8.4
	Dried	3.50	0.30	8.7	3.60	0.28	7.9
				Grain thickness			
	Initial	2.68	0.18	6.9	2.73	0.21	7.6
Barley	Wet	2.72	0.19	7.1	2.81	0.25	8.8
	Dried	2.63	0.18	6.7	2.71	0.22	8.0
	Initial	1.86	0.13	7.0	1.96	0.18	9.0
Oat	Wet	1.94	0.16	8.1	1.95	0.23	11.7
	Dried	1.87	0.13	7.2	1.94	0.14	7.3
	Initial	2.74	0.28	10.1	2.65	0.24	9.2
Rye	Wet	2.71	0.30	11.2	2.66	0.26	9.9
	Dried	2.73	0.25	9.2	2.61	0.24	9.3
	Initial	2.86	0.21	7.3	2.86	0.21	7.3
Fermi	Wet	2.86	0.23	8.0	2.89	0.31	10.8
	Dried	2.85	0.18	6.5	2.80	0.22	7.8
	Initial	2.97	0.21	7.0	3.02	0.20	6.8
Sultan	Wet	3.01	0.22	7.2	3.03	0.28	9.2
	Dried	2.95	0.22	7.6	3.03	0.19	6.2

MV – mean values, *SD* – standard deviations (g) and the coefficient of variation ($CV = 100\frac{SD}{MV}$) (%).

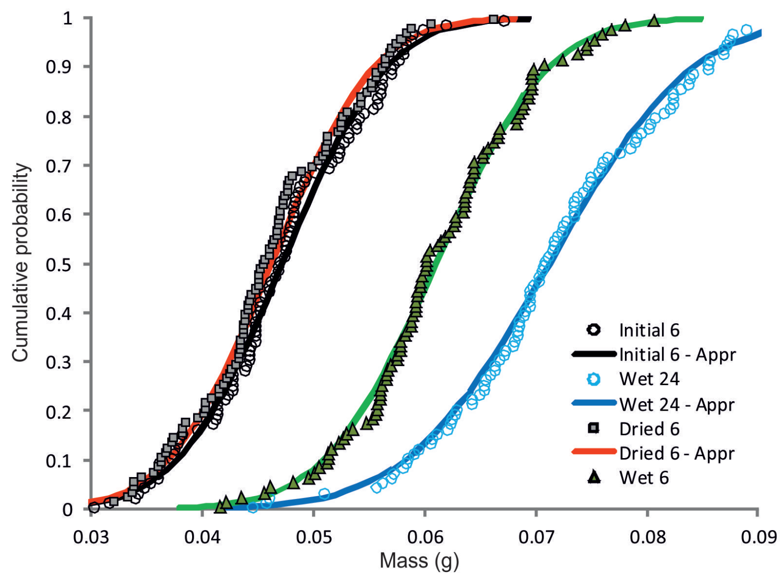

Fig. 1. Cumulative probability of grain mass plotted against the mass value. The plots were obtained for barley in the test with 6-h wetting. The results after 24-h wetting are added, too. All results are approximated by normal distribution based on the values obtained for the mean value and standard deviation.

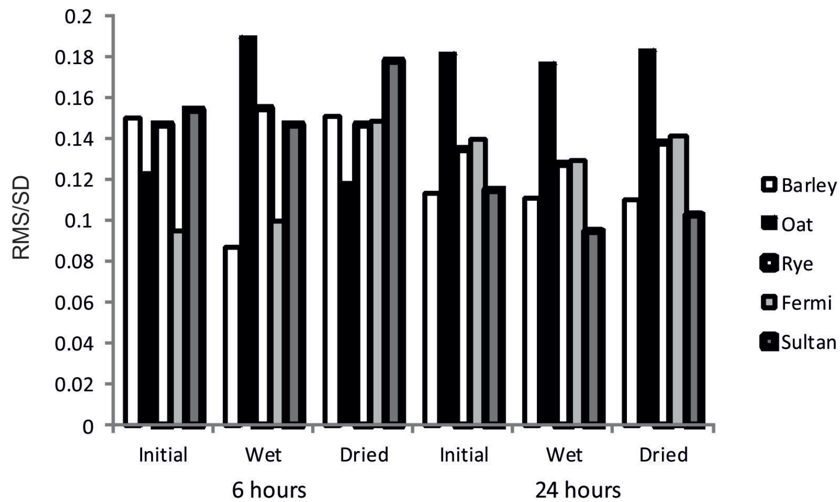

Fig. 2. Ratio of *RMS* (root mean square error) for data in cumulative distribution approximated by Gaussian formula and standard deviation of the mass data. Explanations as in Fig. 1.

of the calculated $\frac{RMS}{SD}$, but with values well below 0.2 (and higher than 0.08). This means that the contribution of stochastic deviations in the whole variation of the measured data is less than 20%, resulting into the *MSD* (model standard deviation) $\approx RMS \leq 0.2\ CV\ MV \leq 0.4\ MV$, a value that is on the border of measurability in our experiments (0.001 g for mass and 0.04-0.2 mm for dimensions). These results support our hypothesis that the measured parameters of the grains can be well described by the Gaussian distribution.

The Gaussian characteristics are useful for describing the relations between two different measurements, *eg* the relation between the same parameter of particular crop grains, but at a different moisture state. Let us have two states of crop grains, I and II, and their properties x are described by the Gaussian parameters as MV_{xI}, SD_{xI}, and MV_{xII}, SD_{xII}. Point x_0 where the standard normal distributions corresponding to both Gaussian plots are equal to one another can be defined as the relative crossing point (*CP*) of the distribution, *ie*:

$$(x_0 - MV_{xI})/SD_{xI} = (x_0 - MV_{xII})/SD_{xII}, \quad (2)$$

giving the formula:

$$CP = \frac{x_0}{MV_{xI}} = \frac{SD_{xII}/SD_{xI} - MV_{xII}/MV_{xI}}{SD_{xII}/SD_{xI} - 1}. \quad (3)$$

Other important parameters describing the properties of distributions are their standard deviations and the relation between the standard deviations of the parameters in two states can be described by their ratio: ratio of standard deviations (*RSD*):

$$RSD = \frac{SD_{xII}}{SD_{xI}}. \quad (4)$$

The results of *CP* and *RSD* obtained for the measurement of mass are given in Table 2. This Table shows that the *RSD* values of wet and initial specimens (SD_{wet} over $SD_{initial}$) are higher than 1, which indicates that the mass of heavier seeds increased more in both the 6 and 24-h tests. The relative crossing points were observed to have very low values in all tested crops. In some cases, negative values were observed, which means that the initial cumulative Gauss probability for the wet and initial measurements are divergent from the very low grain masses, being nearly everywhere higher in the wet than in the initial states (Fig. 1 for barley). The increasing mass of the wet grains was evaluated by the relative change in the grain mass from the initial state to the wet one, *ie* the mass change can be expressed by the relative change in the grain mass (*RCM*):

$$RCM = \frac{m_w - m_i}{m_i} = \frac{m_w}{m_i} - 1. \quad (5)$$

In most cases, this increase depended only slightly on the initial mass, as shown in Fig. 3 for wheat Fermi. The dependence of the relative change in the grain mass on the

Table 2. Dimensionless relations among the parameters characterizing the mass measurements

Crop	W6 - I6		W24 - I24		D6 - I6		D24 - I24	
	CP	*RSD*	*CP*	*RSD*	*CP*	*RSD*	*CP*	*RSD*
Barley	-0.688	1.22	-0.370	1.37	-0.778	1.00	-0.365	0.99
Oat	-0.893	1.17	-0.010	1.39	1.092	1.20	-1.415	0.98
Rye	0.039	1.28	0.133	1.57	-1.362	1.00	0.148	0.98
Fermi	-0.012	1.27	-0.189	1.37	0.759	0.93	-0.006	0.98
Sultan	0.245	1.35	0.236	1.57	1.358	1.06	0.686	0.97

States: initial (*I*), wet (*W*), dried after wetting (*D*), numbers denote time of wetting in hours; *CP* – relative crossing point (related to the initial state), *RSD* – ratio of standard deviations, 6 and 24 denote time of wetting.

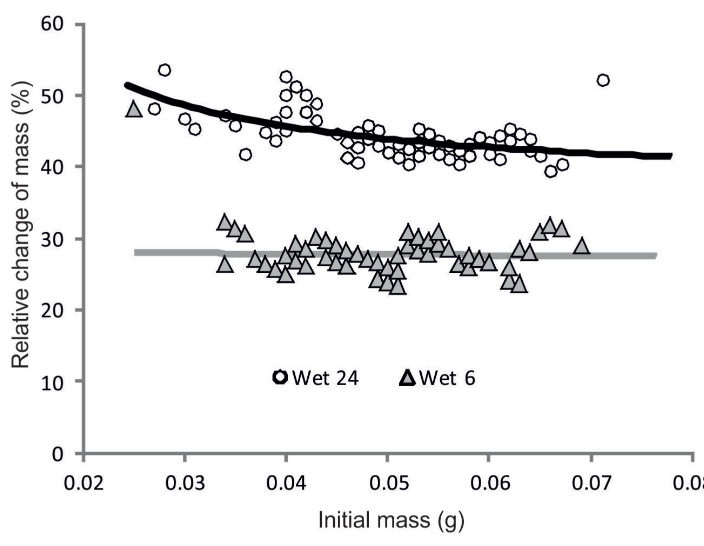

Fig. 3. Relative change in mass during wetting (6 and 24 h) for wheat Fermi plotted versus the initial mass of grains.

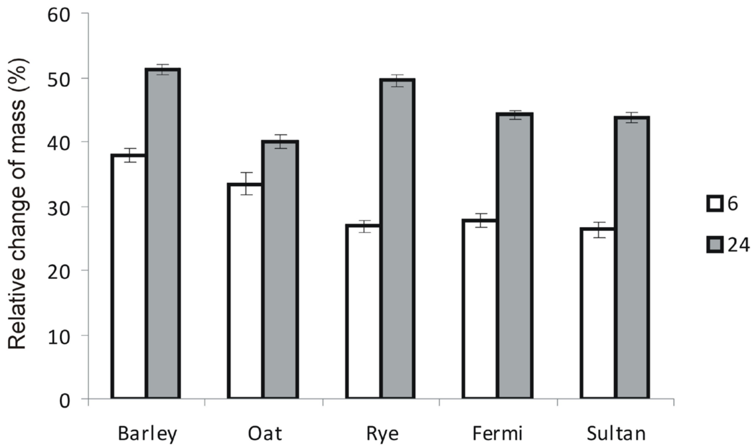

Fig. 4. Relative change in mass during wetting (6 and 24 h) of the tested grains – see Eq. (5). The bars denote standard error of the calculated data.

initial mass of the grains is rather variable for the different crops and it is most pronounced in oat. The overview of the basic measured values is given in Fig. 4. After 6-h wetting, two groups of grains were observed: barley and oat with the highest mass increase (about 33-38%, the highest values in oat were observed in rather small grains) and the other crops with *RCM* of about 27%. After 24-h wetting, three groups of *RCM* were observed: the highest (barley and rye) approximately 50%, middle (wheat) approximately 44%, and the lowest (oat) *ca*. 40%. The results obtained for wheat are in agreement with the data of Rathjen *et al*. (2009). The cumulative distribution functions obtained for the dried mass measurement and the initial mass measurements in the same crop were very similar: the RSD were approximately the same (Table 2). The differences between the initial data and the data for the dried specimens were small. Michailidis *et al*. (2009) showed that even small changes in the mass and volume of individual grains have a consequence in the change in the product bulk density that cannot be simply omitted.

The changes in mass observed during wetting were easily described because the *CP* was always very small and the *RSD* was higher than 1. The resulting cumulative distribution curves for the initial state and the wet one were then shifted one to the other with their shift increasing with the increasing mass of the grains. The changes observed in the dimensions during the wetting of the grains were more complicated. The grain dimensions increased and/or decreased with the increasing moisture content depending on the original grain dimensions. The basic characteristics of the observed relations are given in Table 3 and some explanation of data in Table 4. The observed data plots are classified (Table 4) into the crossing plots, where crossing is observed in the area formed within one standard deviation from the mean value, diverging ones (crossing is below the previous area and the curves diverge one from another with the increasing measured value), and converging ones (crossing above the mentioned area with convergence of the curves with the increasing measured value).

T a b l e 3. Dimensionless relations among the parameters characterizing measurements of grain dimensions

Crop	Grain length				Grain width				Grain thickness			
	W6 - I6		W24 - I24		W6 - I6		W24 - I24		W6 - I6		W24 - I24	
	CP (-)	RSD (-)	CP (-)	RSD (-)	CP (-)	RSD (-)	CP (-)	RSD (-)	CP (-)	RSD (-)	CP (-)	RSD (-)
Barley	1.042	0.91	4.045	0.98	0.955	1.17	1.398	1.19	0.673	1.05	0.847	1.19
Oat	4.900	0.99	0.032	1.05	0.880	1.10	1.182	0.96	0.771	1.20	1.015	1.30
Rye	1.682	0.95	0.539	1.08	0.849	1.12	1.227	1.15	1.102	1.10	0.955	1.08
Fermi	0.443	1.05	0.893	1.36	0.837	1.09	1.139	1.05	1.005	1.09	0.979	1.51
Sultan	0.746	1.15	0.905	1.68	0.449	1.02	1.126	1.01	0.695	1.05	0.986	1.36

Explanations as in Table 2.

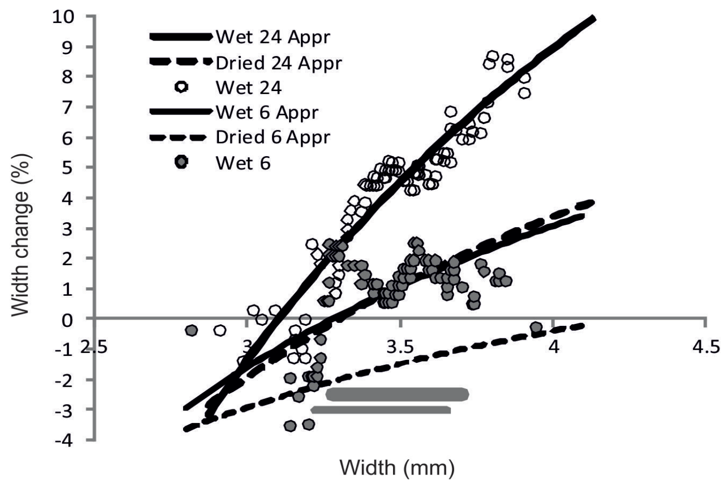

Fig. 5. Relative change in the barley grain during wetting and the following drying. The horizontal axis denotes the initial width, and the vertical axis denotes the relative width change (%) compared to the initial one. The experimental points are approximated by the direct difference of Gaussian approximation of the measured widths (Table 1). This difference is described by quadratic polynomials (Table 5). The grey short lines in the lower part of the figure denote areas of crossing (Table 4) for 6-h wetting (thinner line) and 24-h wetting (thicker line).

The best way to describe the grain dimension changes during wetting thereof and the following drying is to plot the relative dimensional changes versus the initial dimensions as shown in Fig. 5 for the barley grain. The main change in the barley width after 6-h wetting is its increase with its initial value. This dependence is so strong that crossing of the wet and initial dimensions was observed resulting in a decrease in the width dimension during wetting of the small grains. After drying of the wetted grains, the width decreased in some cases to values lower than the initial ones (shrinkage). Longer wetting (24 h) led to a higher dimension increase with conservation of its basic character but changing from the crossing to the diverging state (Table 4). In contrast to wetting, the following drying led to higher dimensions than the initial ones.

T a b l e 4. Basic characteristics of two cumulative functions – for data see Table 3

Character	Type	*CP*	*RSD*
Crossing	IIa	<1-CVx1,1+ CVx1>	> 1
	IIb	<1- CVx1,1+ CVx1>	< 1
Diverging	IIIa	< (1- CVx1)	< 1
	IIIb	< (1- CVx1)	> 1
Converging	IVa	>(1+ CVx1)	> 1
	IVa	>(1+ CVx1)	< 1

CV_{x1} is coefficient of variation of the basic Gauss curve (denoted as 1).

The relative dimensional change δx from state 1 to state 2 can be expressed using Gaussian transformation (Eq. (2)):

$$\delta x = \frac{x_2 - x_1}{x_1} = A + \frac{B}{x_1} \tag{6a}$$

where x_1 and x_2 are dimensions in states 1 and 2, and A and B are characteristic parameters:

$$A = \frac{SD_2 - SD_1}{SD_1} = RSD - 1,$$

$$B = MV_2 - MV_1(1 + A) = MV_2 - MV_1\,RSD, \tag{6b}$$

determined by their mean values (*MV*) and standard deviations (*SD*). The relative dimensional change can be also approximated by a quadratic polynomial:

$$\delta x = a x_1^2 + b x_1 + c\,. \tag{7}$$

with parameters a, b, c. The changes caused by wetting were evaluated using Eq. (7) and the values obtained are given in Table 5.

Equation (7) is suitable for quick evaluation of the relation between δ and x_1. The basic character of the dependence is given by parameter b; positive values for increasing characters and negative for decreasing ones. Parameter a then gives a change in the slope; its positive value represents an increase in the slope with increasing x_1 and *vice versa*. The relative length change δ during imbibition mostly decreased with increasing length (barley, oat, and rye); it slightly increased only in wheat grains. This trend was changed in the germination state where the relative length change

T a b l e 5. Quadratic approximation of the relative difference between wet and initial dimensions

Crop	6 h			24 h		
	a (mm^{-2})	*b* (mm^{-1})	*c* (-)	*a* (mm^{-2})	*b* (mm^{-1})	*c* (-)
			Grain length			
Barley	0.15	-3.60	20.29	0.01	-2.39	18.03
Oat	0.17	-3.39	20.79	0.00	0.07	4.31
Rye	0.16	-3.57	21.28	-0.08	1.81	-5.30
Fermi	-0.06	1.17	-1.89	-0.85	15.82	-61.47
Sultan	-0.30	5.53	-18.94	-1.59	29.86	-118.47
			Grain width			
Barley	-2.97	31.05	-67.85	-1.41	14.59	-32.66
Oat	-1.51	11.34	-17.66	-2.98	23.51	-42.79
Rye	-1.43	11.58	-19.12	-3.21	25.70	-44.86
Fermi	-0.54	6.02	-13.38	-0.87	9.50	-19.98
Sultan	0.09	-0.90	5.25	-0.50	5.31	-5.97
			Grain thickness			
Barley	-0.52	4.20	-5.72	-2.24	18.39	-30.58
Oat	-4.66	25.93	-27.44	-8.30	48.68	-63.41
Rye	-1.61	13.19	-25.06	-1.22	9.65	-16.63
Fermi	-1.19	10.18	-19.47	-6.26	53.70	-101.37
Sultan	-0.42	3.71	-5.77	-4.06	36.69	-73.24

Relative difference δx between wet and initial dimension is approximated by Eq. (6), coefficient of determination R^2 was higher than 0.999.

increased with the increasing dimension (*b* is positive Table 5) in all cases with an exception of barley. Simpler results were obtained for the width and the thickness where nearly in all cases (wheat var. Sultan in imbibition is an exception), an increase in δ with the increasing initial grain dimension was observed (Fig. 5). This means that the width and thickness of swelling grains increased with increasing dimensions. The observed δs are not affected only by the slope parameters but also by parameter *c* in Eq. (7). The δ values obtained can be simply characterized by the relative difference of the mean values:

$$\delta_{MV} = \frac{MV_2 - MV_1}{MV_1} \, , \tag{8}$$

(for mean values see Table 1). This parameter for the initial state (1) and the wet state (2) is plotted in Fig. 6. For the length, a few percent increase was observed during wetting (barley in imbibition is an exception). Similar plots for the width (Fig. 6b) and the thickness (Fig. 6c) are more complicated when observing more variable data including the decrease in the mean values after wetting (oat width and thickness during germination and rye thickness during imbibition). The change in the grain dimensions in a direction perpendicular to the grain axis (width and thickness) during wetting can be expressed as the ratio of δ_{MV} for the thickness and δ_{MV} for the width under the term of wetting asymmetry. This term is plotted for the inspected grains in Fig. 7. Figure 7 shows that the absolute value of the shift asymmetry is less than 1 in many cases; therefore, the relative dimensional change in thickness is less than the same quantity for the grain width. Exceptions were observed only for imbibition of barley and oat.

The lengths of the dried grains after 6-h wetting were mostly lower than the initial ones, which means that the length of the imbibed grains shrank during drying. The observed length changes were below 1%. Similar conclusions can be made for the grain width with one exception:

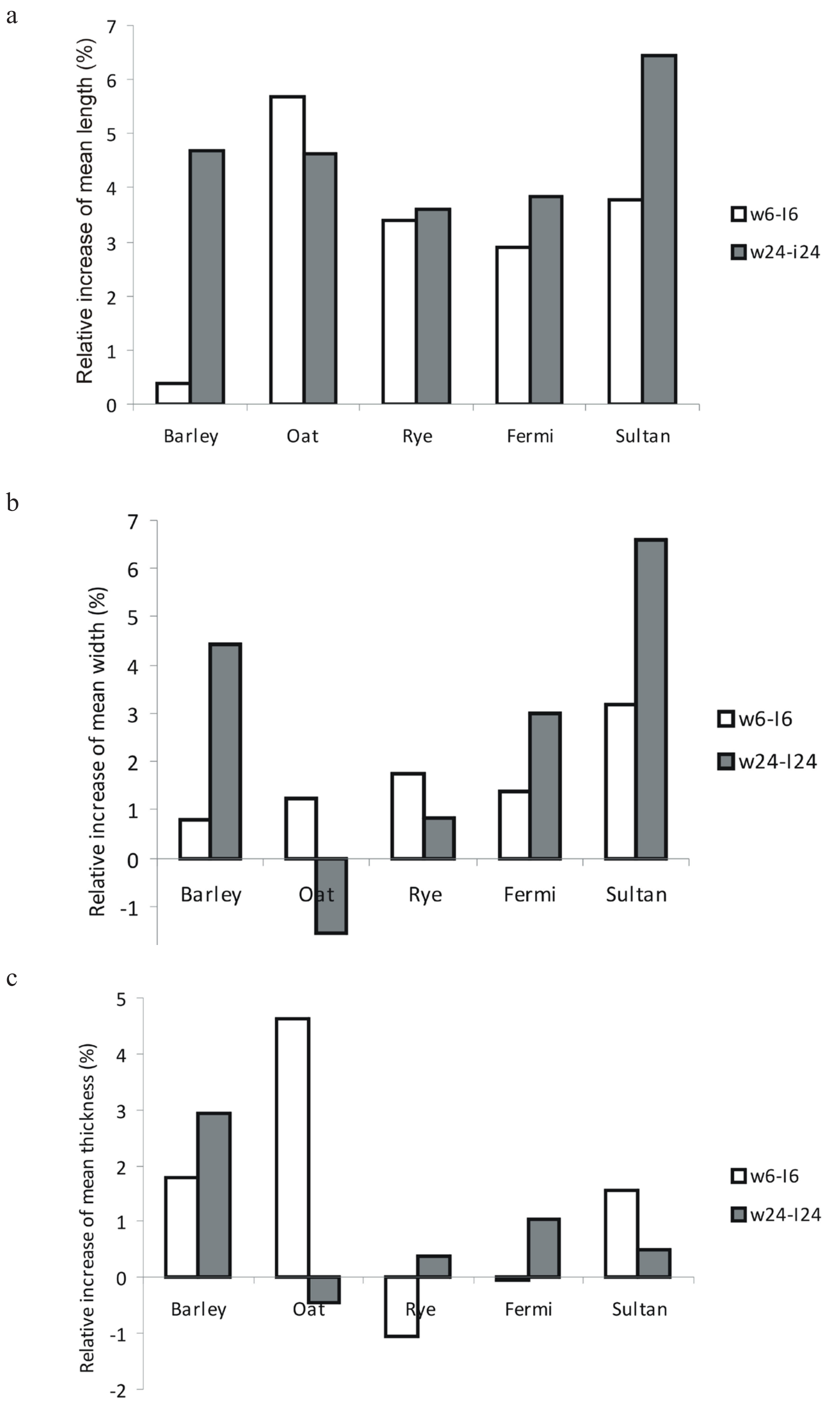

Fig. 6. Relative changes of mean dimensional values during wetting (6 hours – w6, 24 hours w24): a – length, b – width, c – thickness.

barley, where 1.6% shrinking was observed in imbibition and *ca*. 1.3% swelling was observed in germination. The changes in thickness were variable but well below 0.5%.

Our experiments on seed mass yielded similar results as those reported by other authors (*eg* for wheat by Rathjen *et al*., 2009). Our results concerning the dimensional changes can be compared with results obtained by other authors only indirectly using the published mean values and standard deviations of the measured dimensions. Our results indicate that the dimensions and the shape of the imbibed and germinated cereal grains are not simple but depend on details of the internal changes; more detailed information on the shape changes would be useful for a deeper understanding of the whole process of germination in different crops. The authors hope that further research using image analysis will give more information on the dimensional changes in seeds

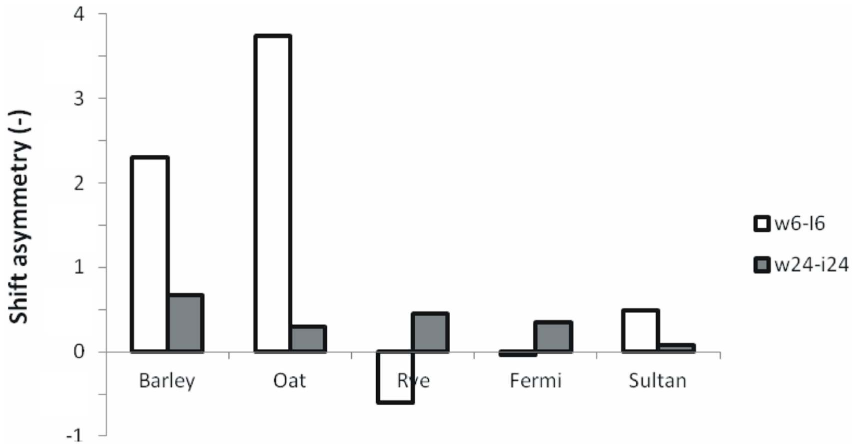

Fig. 7. Wetting asymmetry – ratio of relative change in thickness and relative change in width, the same symbols as in Fig. 6.

during wetting thereof that will be useful not only for a better understanding of details of the seed germination process but also for deeper knowledge of internal stresses in stored cereal products.

CONCLUSIONS

1. The mass and the dimensional variability of wetted cereal grains can be described in terms of Gaussian distribution with errors less than 20% of the total observed variability.

2. The mass and the dimensional parameters for grains of different crops in different states can be compared using crossing point of the distributions andratio of standard deviations.

3. The grain mass increase due to wetting under the same conditions is different for different crops and/or varieties. The highest relative dimension changes due to wetting were observed in the grain length and the lowest relative changes were observed for the grain thickness.

4. The changes in the dimensions depend sensitively on the initial grain dimensions.

5. The dependence of the relative dimensional change can be described by a second-degree polynomial.

6. In some cases, a decrease was observed instead of a dimension increase during wetting.

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