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The determination of impact of malt grist moisture on porosity and permeability using measurement of differential air pressure

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Abstract. This article is focused on determination of malt grist and spent grains porosity and permeability using measurement of differential pressure of the air passing through the layer of malt grist and spent grains. For preparation of malt grist were used different disintegration equipment (two roller mill and disc mill). The method of differential pressure measuring is used for the determination of porosity of malt grist layer, defined as fraction of the volume of voids over the total volume. Measurement confirmed the logical assumption; the higher-pressure difference is above and below the spent grain layer, the lower value of porosity.

Key words: malt grist, special surface area, porosity, permeability, spent grains.

INTRODUCTION

The topic of this article was the determination of impact of malt grist fineness moisture on porosity and permeability using measurement of differential pressure. Both parameters are of great importance for the way of disintegration having significant impact on final structure of malt grist, on quality of filtered first wort and, of course, for final beer. For determination of permeability and porosity of malt grist was used the equipment for measurement of differential pressure above and below the layer of the sample, its flow schema is shown and described in Fig. 3. The topic of porosity and permeability of cereal grist with different roughness was studied and published f.e. by Chládek (Chládek, 1977).

Before the actual mashing process, the malt is mechanically grinded using malt mills (grinders) that work on the principle of grinding between two, four, six pairs counter-rotating roller mills, grinding using rotating hammers and grinding between two discs (so called dispersing reactor Dispax) and wet milling. The product of malt grinding is called a malt crush, which is the basic material for the actual beer brewing (Kunze, 2010; Vaculík et al., 2013, Smejtková et al., 2016).

Basic aspects of milling

In order to give the malt enzymes, the opportunity, during mashing, to act on the malt contents and break them down, the malt must be broken into small fragments. This process is called milling. The disintegrated malt used for a brew is called the malt grist and its amount used is called the charge.

Milling is a mechanical process and within it the husks should be disintegrated carefully because they are lately used in lauter tun as a filter material. A whole series of consideration must be taken into account when fragmenting the malt. But before the malt is milled the amount used is weighed with a weighing machine. The malt is fragmented in a grist mill. Depending on the process used a distinction is made between: dry milling, wet milling, hammer milling, dispersion milling.

In Table 1 and 2 are shown optimal composition of malt grist both for lauter tun mash filter, using both Pfungstädter and MEBAK Plansifter For mash filter is possible to use finer disintegration of malt, allowing shorter time of lauter process.

Table 1. Composition of malt grist using Pfungstädter plansifter

Sieve no.	Fraction	Wire thickness (mm)	Mesh hole size (mm)	
1	husks	0.31 (0.800)	1.270	(1.25)
2	coarse grists	0.26 (0.630)	1.010	(1.00)
3	fine grits I	0.15 (0.315)	0.547	(0.50)
4	fine grits II	0.07 (0.160)	0.253	(0.25)
5	flour	0.04 (0.080)	0.152	(0.125)
Sieve bottom	fine flour	-	-	

The mesh hole size slightly changed by MEBAK (Mitteleuropäische Brautechnische Analysenkommission e. V) lead to the same results. The following grading can be taken as normal values for a good tun or mash vessel grist (Table 2).

Table 2. Composition of malt grist for lauter tun and for mash filter using MEBAK equipment

	Lauter tun grist (%)	Mash filter grist Conventional and Type 2001	
		Conventional,	Type 2001
		(%)	
Sieve 1	18–25	11	1
Sieve 2	< 10	4	2
Sieve 3	35	16	15
Sieve 4	21	43	29
Sieve 5	7	10	24
Sieve bottom	< 1 –15	16	29
Husk volume (mL 100 g^{-1})	> 700	> 650	

During mashing, the enzymes must be able to get at the malt contents in order to degrade them. For this the malt must be broken into smaller pieces. The greater the extent of comminution, the larger the surface area available for enzymic attack and the better the breakdown of the malt material. But after mashing the wort must be run off.

This is a filtration process in which - depending on the mash separation equipment used - the husks are needed as a filter material. Because the husks are required for mash separation (lautering), they must be disintegrated as little as possible during milling. A dry husk fragments easily and filterability is greatly reduced by the small fragments produced by disintegration of the husk. On the other hand, the husk is more elastic the wetter it is and it is then easier to protect. Consequently, lautering is more rapid. The process of wetting the husks is known as conditioning. If a lot of water is added, however, the entire contents of the grain become moist and are then squeezed out of the husk during comminution. This process is known as wet milling. Nowadays the general preference is for a dry endosperm which can be ground as required during milling and, if possible, a moist, elastically deformable husk.

Comminution of the malt depends on its modification. A more modified malt presents little resistance to the grinding roller during milling since the interior of the com is friable and loosely packed. Therefore, the fraction of flour and fine grits is high in the case of well-modified malts. These grits and the flour from well-modified malt sample contain enzymes and readily dissolve later in the brewhouse. Badly modified corn tips and badly modified malt corns are harder and not so easily comminuted. This can be seen from the larger fraction of coarse grits. Because their internal conversion has been retarded they still require extensive enzyme degradation. They release their extract only with difficulty. A smaller yield must therefore be expected if these coarse grits are not completely degraded in the brewhouse:

- milling must be finer the less well modified the malt;
- the degree of comminution has a decisive influence on the volume and filtration efficiency of the spent grains.

ln the case of commonly used lauter vessels the finer the milling the smaller the volume of spent grains, but the finer the grist, the less porous the filter bed, the sooner it becomes pressed together and so the longer the filtration takes.

It can even happen that the wort no longer flows through at all. Consequently, when using a lauter tun, milling must not be too fine, or else the spent grain depth must be reduced if finer milling is used. When a modem mash filter is used none of this applies because the filtration is performed through a very mail pore polypropylene cloth. Therefore, when using such a mash filter the malt can be very finely ground by a hammer mill and very good yields are consequently obtained. The most commonly used mills in breweries are dry grist mills. ln them the malt is crushed in a dry state between rollers arranged in pair. Depending on the number of rollers these are classified as two roller mills, four roller mills, five roller mills, six roller mills, conditioned dry milling equipment and wet milling (Kunze, 2010).

Spent grains

On spent grain discharge, about 100 to 120 kg of spent grains containing 70 to 80% water are obtained from 100 kg of malt grist; this is 21 to 22 kg spent grains h L^{-1} beer. Dried spent grains have approximately the following composition: protein 28.0%, fat 8.2%, nitrogen-free extract 41.0%, cellulose 17.5%, inorganic material 5.3%. The spent grains are sold as cattle food if possible. The nutritional value of spent grain is approximately one-fifth of that of the same amount of barley. This is understandable if one remembers that as much extract as possible is removed during mashing. The advantage of spent grain is its better digestibility compared with the original material. Spent grains do not contain any vitamins and so they cannot be used on their own as animal feed. The spent grains still contain sugar and a lot of protein. Consequently, in warm weather they can easily become sour. There is however not always, or everywhere, a demand for spent grains by neighbouring farmers. In that case, their rapid and satisfactory disposal must be arranged before they turn sour and start to smell. lt is however becoming increasingly difficult for breweries to dispose of spent grains. More and more breweries are therefore starting to dry the spent grains and bum them. As a result of this, a considerable part of the energy used in the brew-house can be recovered. Another way is in fermenting the spent grains and producing biogas, the burning of which can also result in the recovery of energy (Kunze, 2010).

MATERIAL AND METHODS

Procedure for processing samples of malt and malt scrap for measurement purposes

Malt were crushed using following equipment: two roller mill VKM 130/150 with grinding gap adjustments of this mill in the range 0.4 mm (the capacity of the mill is 200.0 kg h^{-1}) and disc mill Skiold SK 2500 (the capacity of the mill is 12,000 kg h^{-1}) (Figs 1, 2 and Table 3).

Figure 1. Two roller mill VKM 130/150.

Figure 2. Disc mill Skiold SK 2500.

Two roller mills for dry milling are used in craft breweries only (Chládek, 2007; Chládek et al., 2013). Because no??? further differentiation of the grist can be obtained with only one pair of rollers during dry milling, optimal yields cannot be obtained (Bogdan & Kordialik-Bogacka, 2017; Chládek et al., 2018). This does not apply to two roller mills used for wet milling or with conditioned malt (Chohan & Garson, 2009; Kunze, 2010).

Table 3. Technical parameters of mills

Two roller mill VKM 130/150		
Type	(-)	two roller mill
Made in	(-)	Czech republic
Grinding gap	(mm)	0.4
Capacity	(kg h^{-1})	200
Disc mill Skiold SK 2500		
Type	(-)	disc mill
Made in	(-)	Denmark
Grinding gap	(mm)	0.0; 0.4
Capacity	(kg h^{-1})	12,000

Next equipment used for measurement was disc mill Skiold SK 2500, supplied by company Skiold Sæby, Denmark (Fig. 2).

The disc mills are mainly used for preliminary and fine grinding of medium-hard and hard-brittle substances (Vaculík et al., 2013; Smejtková et al., 2016).

The experimental measurements were carried out at constant temperature 25 °C and air pressure 968,9 hPa.

Every experiment was repeated 10 times. The average value was calculated and the results are shown in following tables.

Measurement of porosity and permeability of malt grist and spent grains prepared from different malts

Measurement of porosity and permeability of malt grist and spent grains prepared from different malts was published by Chladek 1977.

Definition of porosity is following: porosity or void fraction is a measure of the void (i.e. 'empty') spaces in a material, and is a fraction of the volume of voids over the total volume, between 0 and 1, or as a percentage between 0% and 100% (Basařová, 2010; Kunze, 2010; Kosař & Procházka, 2000).

Parameters of the barley malt shown in the Table 4.

Table 4. Parameters of the barley malt

Variety	(-)	Sladek
Harvest	(year)	2018
Friction angle	(°)	32
Size of whole grain	(mm)	3.65 ± 0.142

The individual weights of the samples in the measuring chamber (Table 8).

Density of the spent grains sample (Feynman et al., 2011):

$$\bar{m} = \frac{m_1+m_2+m_3}{3} \text{ (g)} \quad (1)$$

$$\rho' = \frac{\bar{m}}{V} \text{ (g cm}^{-3}\text{)} \quad (2)$$

$$\varepsilon = 1 - \frac{\rho'}{\rho} \text{ (-)} \quad (3)$$

$$Q = S \cdot v \text{ (m}^3\text{ s}^{-1}\text{)} \quad (4)$$

where $\bar{m}$ – average mass of the sample of the spent grains in the chamber (g); m_1, m_2, m_3 – the individual weights of the samples in the measuring chamber (g); ρ' – volume weight of the spent grains sample (g.cm^{-3}); ρ – density of the spent grains sample (g.cm^{-3}); ε – porosity of dry malt grist (-); S – area of cross-sectional the sample chamber (m^2); v – airflow velocity (m s^{-1}); Q – volume flow of air through the sample (m^3 s^{-1}).

Definition of permeability is following: permeability is the ability of a substance to allow another substance to pass through it, especially the ability of a porous rock, sediment, soil, or material to transmit fluid through pores and cracks. Darcy's law is an equation that describes the flow of a fluid through a porous medium (Feynman et al., 2011; Diyokeugwu & Glover, 2018).

The average dynamic viscosity value $\eta = 18.25.10^{-6}$ Pa.s was used for the calculations. Differential pressures for the dry wheat sample (100% Light barley malt) were experimentally determined for individual samples (Table 5).

Table 5. The resulting values for the calculation of the density of the spent grains sample

Sample no.	$\varDelta p_1$ (Pa)	$\varDelta p_2$ (Pa)	$\varDelta p_3$ (Pa)
1	28.1	27.1	26.2
2	28.2	25.8	26.4
3	28.6	26.6	26.5
4	28.6	25.8	26.1
5	28.9	26.1	26.2
6	29.4	27.7	26.3
7	29.3	27.5	26.3
8	29.5	26.2	26.5
9	28.0	26.4	26.2
10	29.0	26.7	26.1
Mean	28.761	26.59	26.28
Standard deviation.	0.54659451	0.66741625	0.14757296
Coefficient of variation	1.90047115	2.51002725	0.56154093
$\varDelta \bar{p}$ (Pa)	27.21		

Permeability of the spent grains sample is defined by following equation:

$$\varDelta \bar{p} = \frac{\varDelta p_1 + \varDelta p_2 + \varDelta p_3}{3} \text{ (Pa)} \quad (5)$$

$$A = \pi \cdot r^2 \text{ (m}^2\text{)} \quad (6)$$

$$K = \frac{Q \cdot \eta \cdot L}{\varDelta \bar{p} \cdot A} \text{ (m}^2\text{)} \quad (7)$$

where $\varDelta p_1$; $\varDelta p_2$; $\varDelta p_3$ – differential pressures of dry samples (100% barley malt) experimentally determined for individual samples (Pa); $\Delta \bar{p}$ – average value of the differential pressure of the dry barley malt (Pa); r – inside diameter of the measuring chamber (Table 6) (m); A – area of cross section (Table 6) (m^2); L – height of the measuring chamber (Table 6) (m); Q – volume flow of air through the sample (m^3 s^{-1}); η – dynamic air viscosity (10^{-6} Pa.s); K – permeability according to Darcy's relationship (Table 6) (m^2) (Feynman et al., 2011).

Table 6. The resulting values for the calculation of the density of the spent grains sample

r (m)	A (m^2)	L (m)	K (m^2)
0.133	0.056	0.00098	3.9.10^{-7}

The description of laboratory measuring instrument for differential pressure determination

The laboratory measuring instrument was connected according to assembly diagram as shown in Figs 3 and 4. From pressure balloon (1) with pressure reducing valve (2) was pipeline divided, one branch of it was connected with the differential pressure gauge (4), the second branch was connected with the bottom of sample chamber (3). Above the top of sample chamber (3) the pipe-line was again divided, one branch led to the differential pressure gauge (4), second one was connected with the flowmeter (5), from which the measured air escaped free into space. For measurement of the values of differential pressure of the air below and above sample chamber was used differential manometer type Testo 512 (Table 7), supplied by company Conrad (Germany).

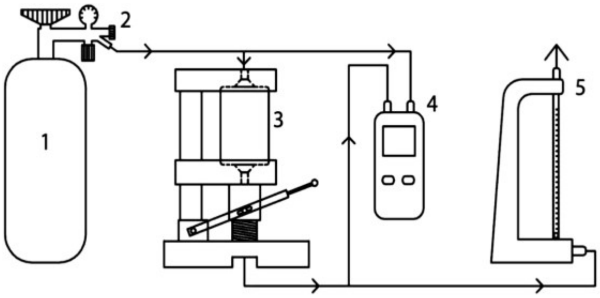

Figure 3. The scheme of the laboratory measuring instrument for differential pressure determination above and below the sample layer: 1 – pressure balloon with compressed air; 2 – pressure reducing valve; 3 – measuring chamber; 4 – differential pressure gauge; 5 – flowmeter.

Figure 4. Measuring assembly for determining differential pressure in samples: 1 – pressure balloon with compressed air; 2 – pressure reducing valve; 3 – measuring chamber; 4 – differential pressure gauge; 5 – flowmeter.

Table 7. Technical parameters of differential manometer Testo 512

Sensor type	(-)	integrated pressure transducer
Measuring range – pressure	(hPa)	0.0–20.0
Measuring range – speed	(m s^{-1})	+ 5.0 – + 55.0
Distinction – pressure	(hPa)	0.001
Distinction – speed	(m s^{-1})	0.1
Dimension (w x d x h)	(mm)	202.0 x 57.0 x 42.0
Weight	(g)	300.0

As the source of the pressured air was used pressure balloon with pressure reducing valve, supplied by company MedX5, its parameters are described in Table 8.

Measurement method:

- before measurement the testing chamber was weighed,
- chamber filling by measured sample up to upper edge, cleaning the upper edge,
- the desired air pressure was adjusted by pressure regulator,
- due to air pressure was sample inside of testing chamber pressed down, that why was chamber refilled up to upper edge,
- after new cleaning the upper edge was the testing chamber was again weighed and put in measurement system,
- the pressure difference at inlet and outlet of air from sample chamber was measured.

Table 8. Technical parameters of a pressure bottle with a regulator

Volume	(l)	9.0
Weight	(kg)	4.8
Operating pressure	(MPa)	30,0
Length	(mm)	628.

RESULTS AND DISCUSSION

According to moisture contentin malt grist and in spent grains, the values of permeability and porosity significantly changed (Table 12). During moisture content varying in measured samples were not found any linear dependence of permeability on water content.

For experimental activities had been used following samples (Table 9):

Table 9. Basic parameters of used equipments

Sample	Mill	Grinding gap (mm)	Distributor roller (-)	Rotation speed (r min^{-1})
Spent grains (100% light barley malt – malt 1)	two roller	0.40	-	200
Spent grains (75% wheat barely malt, 25% dark barley malt - malt 2)	two roller	0.40	-	200
Light barley malt	two roller	0.40	-	200
Light barley malt	disc	0.40	1/3	2,800
Light barley malt	disc	0.15	1/3	2,800
Light barley malt	disc	0.15	2/3	2,800

The individual weights of the samples in the measuring chamber: $m_1 = 10.61$ g; $m_2 = 9.93$ g; $m_3 = 9.49$ g (Table 10).

Table 10. Dimensions of the measuring chamber and resulting values for the calculation of the density of the spent grains sample

Diameter d (mm)	Height h (mm)	Volume V (mm^3)	
17.57	56.8	55,086.0	
Average mass $\overline{m}$ (g)	Volume weight ρ' (g cm^{-3})	Porosity ε (-)	Volume flow Q (m^3 s^{-1})
10.00	0.176	0.863	0.0095

As shown in the Table 12 there is a comparison of two samples of brewery-spent grains. The values of permeability of measured samples did not differ from one another. The higher value of permeability $3.09.10^{-8}$ m^2 was shown, only by spent grains gained from light malt (spent grain 1), while the permeability of second sample from spent grains brewed the combination of light and Bavarian malt was determined $2.86.10^{-8}$ m^2. This explains the significantly longer time of lautering process of sweet wort, using as a raw material next to light malt as well Bavarian, caramel and colour ones. Due to higher temperature of kilning in malt plant its texture is more fragile causing the decrease its permeability.

Every experiment was repeated 10 times. The average value was calculated and the results are listed in tables (Table 11 and 12).

Measurement confirmed the logical assumption; the higher-pressure difference above and below the spent grain layer, the lower value of porosity and permeability.

The values of permeability of sample No. 1 were in the range $4.11.10^{-7}$ m^2 up to $3.09.10^{-7}$ and porosity 0.85 up to 0.45. The values of permeability of sample No. 2 were in the range $3.69.10^{-7}$ m^2 up to $2.86.10^{-7}$ and porosity 0.83 up to 0.36 (all those figures are the average of tens measurements).

Measured values correspond with the results published in article ‘Alternatives to malt in brewing’ (Bogdan & Kordialik-Bogacka, 2017), ‘Pivovarství’ (Basařová, 2010) and others.

Table 11. Permeability and porosity values for different moisture content in malt grist

Type of mill	Two roller mill	Disc Mill	Disc mill	Disc mill	Disc mill
Grinding gap	0.4 mm	0.4 mm	0.4 mm	0.0 mm	0.0 mm
Distributor roller	-	1/3	2/3	1/3	2/3
Permeability and porosity values for dry malt grist (moisture content 4%)					
Porosity	0.64	0.55	0.62	0.55	0.48
Permeability	$1.17.10^{-7}$	$2.72.10^{-9}$	$3.73.10^{-9}$	$1.14.10^{-9}$	$5.81.10^{-9}$
Permeability and porosity values for malt grist (moisture content 45%)					
Porosity	0.51	0.54	0.42	0.38	0.43
Permeability	$1.14.10^{-7}$	$1.52.10^{-7}$	$1.70.10^{-7}$	$1.79.10^{-7}$	$9.73.10^{-8}$
Permeability and porosity values for malt grist (moisture content 50%)					
Porosity	0.31	0.33	0.29	0.27	0.28
Permeability	$1.05.10^{-8}$	$1.24.10^{-8}$	$2.08.10^{-8}$	$2.12.10^{-8}$	$2.38.10^{-8}$
Permeability and porosity values for malt grist (moisture content 60%)					
Porosity	0.30	0.32	0.28	0.26	0.27
Permeability	$1.32.10^{-8}$	$1.58.10^{-8}$	$2.56.10^{-8}$	$3.21.10^{-8}$	$3.52.10^{-8}$
Permeability and porosity values for malt grist (moisture content 65%)					
Porosity	0.39	0.31	0.22	0.24	0.22
Permeability	$3.48.10^{-8}$	$2.14.10^{-8}$	$3.11.10^{-8}$	$3.56.10^{-8}$	$4.24.10^{-8}$

Table 12. Comparison of permeability, porosity, moisture content and differential pressures of samples of grain

Malt (Table 9)			Moisture content in the malt					
			0	45	50	60	65	80
			(%)					
Sample 1	Δp	(hPa)	0.26	0.30	0.32	0.39	0.42	0.57
	Porosity	(-)	0.85	0.74	0.81	0.69	0.72	0.45
	Permeability	(m^2)	$4.11.10^{-7}$	$3.76.10^{-7}$	$3.62.10^{-7}$	$.3.50.10^{-7}$	$3.25.10^{-7}$	$3.09.10^{-7}$
Sample 2	Δp	(hPa)	0.27	0.31	0.38	0.57	0.68	0.74
	Porosity	(-)	0.83	0.70	0.73	0.65	0.62	0.36
	Permeability	(m^2)	$3.69.10^{-7}$	$3.59.10^{-7}$	$3.46.10^{-7}$	$3.19.10^{-7}$	$3.02.10^{-7}$	$2.86.10^{-7}$

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