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The temperature changes of barley malt during its disintegration on a two roller mill

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Abstract. This article discusses the change of temperature during disintegration on two roller mill. The production of barley and its treatment to malt is first step of beer brewing. The malt is the produced in malt plants. Crushing the malt is realized in only the brewery and is a core activity of brewing technology. This operation is performed both in craft breweries and in industrial brewery. This article therefore is focused on the theory of crashing solid phase with a respect of development of heat. Grinding barley malt is realised using mills of various designs or disintegrators. They are widely used mills with 2, 4, 5, 6 grinding cylinders. These roller mills are used in many other applications, not only in industrial food or drink production. For next treatment solid phase should be broken into smaller pieces (comminuted). The greater the extent of comminution, the large the surface area for impact on next treatment. The amount of mechanical energy converted to heat energy depends on the principle of the process disintegration and other parameters, i.e. distance of grinding gap, capacity, mechanical properties of crashing material etc. For these reasons, it is important to pay attention to the temperature change of barley malt during its disintegration on a mill.

Key words: temperature, barley malt, two roller mill, grinding cylinders, disintegration.

INTRODUCTION

Machines based on the principle of grain grinding by means of rollers are the most frequent grinding machines used in grain mills (it concerns so-called grinding rolling mills) and their derived constructions are used in a number of other food processing industrial sectors (Smejtková & Chládek, 2012). Roller crushers (mills) can be also used in beer production technologies for malt crushing at the very beginning of the beer production. The main working bodies of roller crushers are milling rollers the surface of which is adjusted in various ways. When crushing particles between the rollers, pressure, friction and cutting forces are applied. The grist is usually transported to the grinding space by means of feeding equipment, most frequently equipped with rollers. Grinding roller machines usually consist of a box, feeding equipment, storing equipment (side and central), grinding rollers equipped with roller surface cleaning equipment, gears and motor (Vaculík et al., 2010). Folding equipment enables adjusting of the grinding joint and of the parallel position of rollers (Chládek et al., 2013, Přikryl et al. 2015).

MATERIAL AND METHODS

The crushing process takes part in the grinding space where the grain is held and processed. Subsequently its fragments are passed through the place where the rollers get the closest together, by the so-called grinding gap. The size of the roller averages affects the grinding space area (Kulp & Ponte, 2000). The crushing intensity can be effectively regulated by changing the gap size. The grinding performance is affected by the length of the rollers and this length must be adjusted so that the rollers are not too long, as in such case they would be subject to deformation (deflexion) (Dendy & Dobraszczyk, 2001; Kalnina et al., 2015). The roller surface finish is grooved, the polished rollers being grooved on special grooving machines. Grinding executed by grain processing with grooved rollers in a mill is a kinetic process during which the grains are held by a low speed (holding roller) and processed by a high roller (crushing roller) with a greater peripheral speed (it concerns a frequent construction of the machine when the grinding rollers in the crusher rotate against each other with differing peripheral speed) (Vaculík et al., 2013). This process is affected by a number of factors ensuing from geometrical and kinematic characteristics, as well as from physical characteristics of the barley malt, which can be defined only with difficulty. The crusher works in a complex way mainly at the level of the grinding gap (Kent & Evers, 1994). The malt grains entering the grinding space are exposed to forces originating on the surface of the rollers and also affecting the other parts of the two-roller mill. The determination of the wattage is based on the precondition of a force F_B passing through centre of gravity, which originates on the surface of the rollers and is applied in the axis passing through the centre of gravity of the rolling space. This axis is parallel with the axis passing through the centres of the rollers. For a horizontal setting of the roller axes the centre of gravity is located in δ distance. Pressure applied by F_B force on the surface of the rollers creates $F_B.\ \delta$ moment acting against the direction of the roller rotation (Fig. 2) (Maloun, 2001).

To monitor the heat changes in barley malt during crushing using a two-roller mill we selected two-roller mill (crusher) KVM 130/150, thermal recorder IR FlexCam Ti35 and digital thermometer COMMETER D3121.

The basic characteristic of the used barley malt is as follows. It is a product made of barley after four- or five-week maturation in containers. The malt production technology includes at the beginning pre-cleaning of barley followed by barley steeping in special tanks, so-called steep tanks, barley germination and kilning (i.e. drying) of the germinated malt in a kiln. Such germinated but still green malt is first dried by air 60 °C (final water content 3–4%). After the kilning procedure termination dried malt is cleansed from damaged grains, dust and roots and transported to a container in which it must rest before the subsequent processing for a certain period. The basic technical parameters of two-roller mill KVM 130/150 (Fig. 1) are as following: two-roller mill; machine performance (0.044 kg s^{-1}); width of roller gap (0.4 mm); measurable specific heat of barley malt (c_{malt} = 1.35 kJ kg^{-1} K^{-1}. The specific heat of barley malt c_{malt} was measured in our laboratory calorimeter five times average value was 1.35 kJ kg^{-1} K^{-1}. Literature (Manger, H.-J, 1999) specific heat of barley with humidity 0& indicated 1.55 kJ kg^{-1} K^{-1}; standard deviation ± 2%. The correlations of theoretical and experimental values are very good.

The basic technical parameters of thermal recorder IR FlexCam Ti35 are as follows: high temperature sensitiveness to display even the slightest temperature differences (≤ 0.1ºC); temperature range suitable for a wide choice of industrial applications (-20 °C to +350 °C); flexible lenses movable in the extent of 180º to view pictures in any situation; a large 125 mm contract colour LCD display.

Figure 1. Malt mill KVM 130/150 (author's archive).

The basic technical parameters of digital thermometer COMMETER D3121 (with an external probe on the cable) designated for measurement and recording of temperatures are as follows: temperature range (-30 °C up to +105 °C); great thermal sensitivity (0.1 °C) and accuracy (±0.4 °C).

The torque moment is described as:

$$M_0 = F_B \cdot \delta \tag{1}$$

where: M_0 – torque moment (N m); F_B – is the force passing through the centre of gravity (N); δ – distance of the applied force passing through the centre of gravity F_B from the centre of gravity of the grinding roller axes (m).

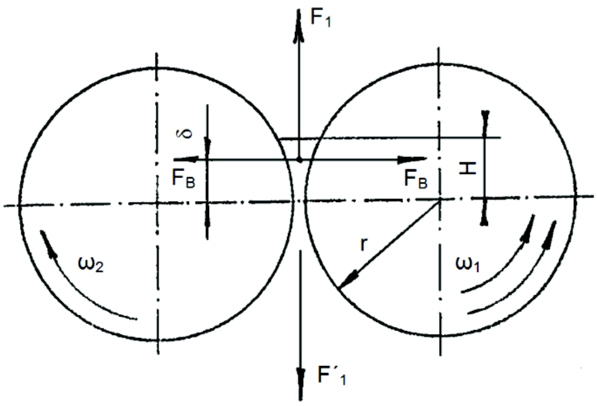

Figure 2 Grinding rollers and force passing through the centre of gravity (Maloun, 2001): F_B – force passing through the centre of gravity (N); $F_1{'}$ – resulting tangential force applied on the low-speed (holding) roller (N); F_1 – resulting tangential force applied on the high-speed (crushing) roller (N); r – grinding roller radius (m); H – grinding gap height (m); δ – distance of the applied force passing through the centre of gravity from the centre of gravity of the grinding roller axes (m); ω_1 – angular velocity of the high-speed roller (rad s^{-1}), ω_2 – angular velocity of the low-speed roller (rad s^{-1}).

Tangential force F_d is described as:

$$F_d = F_B \cdot \frac{\delta}{r} \tag{2}$$

where: F_d – tangential force (N); F_B – force passing through the centre of gravity (N); δ – distance of the applied force passing through the centre of gravity from the centre of gravity of the grinding roller axes (m); r – roller radius (m).

The high speed roller rotates in opposite direction as low speed one with differing peripheral speeds. When the malt grist passes through the grinding space, another tangential force F_t is originating due to the friction of the grist fragments on the roller cutting edges. In compliance with the force definition it can be expressed as follows:

$$F_t = F_B \cdot tg\ \varphi \tag{3}$$

where: F_t – tangential (friction) force (N); F_B – force passing through the centre of gravity (N); φ – friction angle (°).

Forces F_d and F_t are summed up algebraically. It ensues from the theoretic analysis of the originating mechanical tensions that the pressure of force F_B originating on the entire surface of the ground material (along the length of roller L) affects the diameter of the rollers with radius r by means of tangential force F_d applied against their rotation. The moving of the grains in the high speed roller is slowed down by means of the low speed roller (with slower rotation) on the entire surface of the ground material by means of tangential (friction) force F_t. The resulting tangential force applied on the grinding high speed roller can be expressed as:

$$F_1 = F_B \cdot tg\ \varphi + F_B \cdot \frac{\delta}{r} = F_B \cdot \left(tg\ \varphi + \frac{\delta}{r} \right) \tag{4}$$

where: F_1 – resulting tangential force applied on the high-speed (crushing) roller (N); F_B – force passing through the centre of gravity (N); φ – friction angle (°); δ – distance of the applied force passing through the centre of gravity from the centre of gravity of the grinding roller axes (m); r – roller radius (m).

The resulting force ion low speed roller is described as:

$$F_1' = F_B \cdot tg\ \varphi - F_B \cdot \frac{\delta}{r} = F_B \cdot \left(tg\ \varphi - \frac{\delta}{r} \right) \tag{5}$$

where: F_1' – resulting tangential force applied on the low speed (holding) roller (N); F_B – force passing through the centre of gravity (N); φ – friction angle (°); δ – distance of the applied force passing through the centre of gravity from the centre of gravity of the high speed roller axes (m); r – grinding roller radius (m) (Maloun, 2001; Feynman et al., 2011).

The torque moment ensuing from the compound forces applied on the high speed roller:

$$M_1 = F_B \cdot r \cdot \left(tg\ \varphi + \frac{\delta}{r} \right) \tag{6}$$

where: M_1 – torque moment ensuing from the compound forces applied on the high speed roller (N m); F_B – is the force passing through the centre of gravity (N); φ – friction angle (°); δ – distance of the applied force passing through the centre of gravity F_B from the centre of gravity of the high speed roller axes (m); r – high speed roller radius (m).

The torque moment M_2 passes from the low speed roller to the high speed roller describes as:

$$M_2 = \frac{F_B \cdot r \cdot \left(tg\,\varphi - \frac{\delta}{r} \right)}{K} \tag{7}$$

$$K = \frac{v_{hs}}{v_{ls}} \tag{8}$$

where: M_2 – torque ensuing from the compound forces applied on the crushing roller (N.m); F_B – is the force passing through the centre of gravity (N); r – grinding roller radius (m); φ – friction angle (°); K – ratio v_{hs}/v_{ls} (–); δ – distance of the applied force passing through the centre of gravity F_B from the centre of gravity of the grinding roller axes (m); v_{hs} – peripheral velocity of the high speed roller (m s^{-1}); v_{ls} – peripheral velocity of the low speed roller (m s^{-1}).

When processing the malt grains the high speed roller requires that the torque moment of the mill has the following value:

$$M_3 = M_1 - M_2 \tag{9}$$

where: M_3 – torque moment of the mill (N m); M_1 – torque moment ensuing from the compound forces applied on the crushing roller (N m); M_2 – torque moment passes from the low speed roller to the crushing roller (N m).

At the angular speed of the high speed roller of ω_1 the performance of the electromotor described as:

$$P_w = M_3 \cdot \omega_1 \tag{10}$$

where: P_w – power of electomotor (W); ω_1 – angular velocity of the high speed roller (rad s^{-1}); M_3 – torque moment of the mill (N m).

The performance needed to drive the rollers can be determined based on the following relation:

$$P_w = \frac{\pi}{30} \cdot \left[T \cdot r \cdot (n_1 - n_2) + N \cdot \delta \cdot (n_1 + n_2) \right] \tag{11}$$

$$n_1 = \frac{30 \cdot \omega_1}{\pi} \tag{12}$$

$$n_2 = \frac{30 \cdot \omega_2}{\pi \cdot K} \tag{13}$$

where: T is $T = F_B \,.\, tg\,\varphi$ (N) and $N = F_B$ (N); n_1 – number of rotations of the high speed roller (min^{-1}); n_2 – number of rotations of the low speed roller (min^{-1}); φ – friction angle (°); K – ratio v_{hs}/v_{ls} (–); δ – distance of the applied force passing through the centre of gravity F_B from the centre of gravity of the grinding roller axes (m); ω_1 – angular velocity of the high speed roller (rad s^{-1}); ω_2 – angular velocity of the low speed roller (rad s^{-1}).

The performance of the roller mills can be determined according to the following relations, while the theoretic mass flow of the grist through the roller mill can be determined as:

$$R = s \cdot l \cdot v_{str} \cdot \rho \cdot \psi \tag{14}$$

$$v_{str} = \frac{v_r + v_p}{2} \tag{15}$$

where: s – grinding gap (m); l – length of rollers (m); v_{str} – medium speed of the grist in the grinding gap (m s^{-1}); ρ – volume weight of the grist (kg m^{-3}); ψ – coefficient of the grinding space filling (–); v_r – peripheral velocity of the high speed roller (rad s^{-1}); v_p – peripheral velocity of the low speed roller (rad s^{-1}).

According natural laws two bodies not chemically affecting each other balance their temperatures upon mutual contact. This phenomenon can be explained in the way that a certain value of heat passes from the substance with a higher temperature to the substance with a lower temperature and both temperatures equilibration. When the temperature of two interfering bodies levels off, the resulting temperature does not represent an average of both temperatures; not even in the case when we take into account the weight of such bodies. It has occurred that different times are needed when using the same heater to heat the same amount of different substances to the same temperature. Therefore the term thermal amount Q has been established, which is defined as the product of weight m, constant c and temperature T (while according to the law of energy conservation at the resulting temperature t the heat accepted by the cooler body must equal the heat surrendered by the warmer body).

The heat transfer from bodies with higher temperature to the surrounding with lower temperature occurs in three ways: by conduction, convection and radiation. Conduction spreads heat in a substance which can have a solid, liquid or gaseous form. During this heat transfer molecules in places with higher temperature have a greater kinetic energy which is partially surrendered to the neighbouring molecules without any moves in the surrounding (free electrons contribute to this transfer in metals).

The amount of heat Q passing through area S for time τ in a substance with thickness d, provided that a fixed temperature differential is maintained on both sides of the layer ($t - t_0$), is established by the following relation:

$$Q = \lambda \cdot S \cdot \tau \cdot \frac{t - t_0}{d} \tag{16}$$

where: Q – the heat needed for heating (J); S – area (m^2); τ – time (s); λ – thermal conductivity of the given substance (J m^{-1}.s^{-1}) ; t – final temperature (°C); t_0 – initial temperature (°C); d – thickness (m).

Thermal conductivity represents the amount of heat which passes through the area of 1 m^2 per one second at the temperature differential of 1 °C per 1 m.

$$Q = m \cdot c \cdot \Delta T \tag{17}$$

$$\Delta T = T_2 - T_1 \tag{18}$$

where: Q – the heat needed for heating (J); m – weight of the malt sample (kg); c – specific heat (J kg^{-1} K^{-1}); ΔT – temperature difference (K); T_2 – final temperature of the malt sample (K); T_1 – initial temperature of the malt sample (K).

The arithmetic average was used for evaluation of the measurement. The arithmetic average is defined as being equal to the sum of the numerical values of each and every observation divided by the total number of observations. Symbolically, if we have a data set containing the values a_1... a_n. The arithmetic average is defined as:

$$\phi = \frac{1}{n}\sum_{i=1}^{n} a_i \tag{19}$$

where: $\varnothing$ – arithmetic average (–); a_1,..., a_n – the values of data set (Maloun, 2001; Feynman et al., 2011).

RESULTS AND DISCUSSION

The Figs 3 and 4 provide pictures performed by the thermal recorder during barley malt grinding at two-roller mill KVM 130/150.

The following table (Table 1) shows the measured temperature values during barley malt grinding on two-roller mill KVM 130/150 in the course of five measurements. The provided values of the particular temperatures were measured before the grinding initiation (i.e. time 0 min.) during grinding of 13.3 kg of grist (i.e. 5 minutes after the grinding initiation) and at fixed temperatures, which corresponds to grinding of 160 kg of grist (i.e. in 60 minutes).

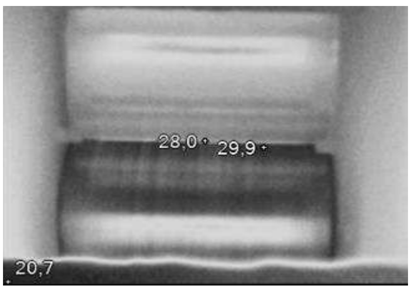

Figure 3. Temperatures of grinding rollers (60 min of grinding) (author's archive).

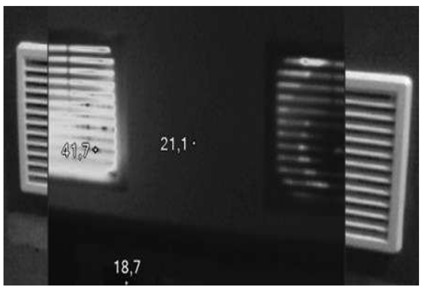

Figure 4. Temperatures of the mill outer surface (60 min of grinding) (author's archive).

Table 1. Measured temperature values during barley malt grinding on two-roller mill KVM 130/150

Measurement number	1			2			3			4			5		
Temp. (°C)	T*	TR*	**Ø1***	T*	TR*	**Ø2***	T*	TR*	**Ø3***	T*	TR*	**Ø4***	T*	TR*	**Ø5***
Air in the room	18.0	18.0	**18.0**	19.0	19.0	**19.0**	18.0	18.0	**18.0**	19.5	19.5	**19.5**	18.5	18.5	**18.5**
Time 0 minutes (i.e. before grinding initiation)															
Machine external	18.0	18.0	**18.0**	19.0	19.0	**19.0**	18.0	18.0	**18.0**	19.5	19.5	**19.5**	18.5	18.5	**18.5**
Machine rollers	18.3	18.9	**18.6**	19.4	19.8	**19.6**	18.6	19.0	**18.8**	20.0	20.2	**20.1**	18.7	18.3	**18.5**
Malt before crushing	19.4	18.8	**19.1**	18.8	19.3	**19.1**	17.7	17.8	**17.8**	19.4	19.2	**19.3**	19.4	19.6	**19.5**
Time +5 minutes (i.e. 5 minutes of crushing = 13.3 kg grist)															
Malt after crushing	20.9	20.2	**20.6**	21.1	20.9	**21.0**	20.8	21.0	**20.9**	21.9	21.7	**21.8**	20.6	20.4	**20.5**
Machine rollers	20.6	20.6	**20.6**	21.5	21.3	**21.4**	20.8	20.4	**20.6**	22.2	22.4	**22.3**	21.0	20.9	**21.0**
Barley malt in hopper	18.8	18.4	**18.6**	18.8	19.0	**18.9**	19.0	18.6	**18.8**	20.0	20.0	**20.0**	18.8	18.4	**18.6**
Temperature differential of malt and grist after 5 minutes of grinding															
	-	-	**2.0**	-	-	**2.1**	-	-	**2.1**	-	-	**1.8**	-	-	**1.9**
Arithmetic average of temperature different															**1.98**
Time +60 min (i.e. 60 min of crushing = 160 kg grist) (settled temperature)															
Malt after crushing	21.4	21.2	**21.3**	21.5	21.3	**21.4**	21.3	21.6	**21.5**	22.6	22.4	**22.5**	21.2	21.6	**21.4**
Machine rollers	28.1	27.9	**28.0**	27.8	28.0	**28.0**	28.4	28.0	**28.2**	29.5	30.1	**29.8**	27.3	27.5	**27.4**
Barley malt in hopper	17.8	18.2	**18.0**	17.6	18.0	**17.8**	17.8	18.2	**18.0**	19.7	19.3	**19.5**	18.0	17.8	**17.9**
Temperature differential of malt and grist after 60 minutes of grinding at fixed temperature															
	-	-	**3.3**	-	-	**3.6**	-	-	**3.5**	-	-	**3.0**	-	-	**3.5**
Total arithmetic average of temperature different															**3.38**

*Explanatory notes:
T – thermometer; TR – thermal recorder; Ø – arithmetic average of measurement values.

Experimental measured values have been evaluated statistically using program in computer.

Theoretical calculation of the theoretical heat needed for heating and the measured heat needed for heating as follows from the equation 16:

$$Q_1 = m \cdot c_{malt1} \cdot \Delta T = 160 \cdot 1{,}55 \cdot 3{,}38 = 838{,}24\,K \qquad (20)$$

$$Q_2 = m \cdot c_{malt2} \cdot \Delta T = 160 \cdot 1{,}35 \cdot 3{,}38 = 730{,}08\,K \qquad (21)$$

where: Q_1 – the theoretical heat needed for heating (J); Q_2 – the measured heat needed for heating (J); m – weight of the barley malt sample (kg); c_{malt1} – theoretical specific heat of barley malt (J kg^{-1} K^{-1}); c_{malt2} – measured specific heat of barley malt (J kg^{-1} K^{-1}); ΔT – temperature difference (K) (Manger, H.-J, 1999; Feynman et al., 2011).

CONCLUSION

When grinding using blows (i.e. when grinding by means of hammer crushers that are also used to process barley malt for the beer production) less than 5 percents of wattage are used for the disintegration itself, while 95% are not related with disintegration at all; it is wasted energy dissipating into heat and causing heating of the ground material and/or the machine body. When using the same material to be ground – barley malt and with the same parameters of the input product the grist after grinding on the hammer crusher was heated up by 8.5 K to 15 K (according to the type of crusher used). By measuring the barley malt grinding on two-roller mill KVM 130/150 we found out that the average heating of the resulting grist (at fixed temperature values) reaches 3.38 K.

The obtained experimental results are in good correlation with theoretical assumption, as shown in table 1.

This value (with the measurable energy consumption of 4.46 kJ kg^{-1}) is not significant, as regards influencing of the grinding process, the technical parameters of the mill and the resulting characteristics of the grist, and it confirms that using of roller mills for the malt crushing while maintaining the required characteristics of the resulting grist (the grist structure) is beneficial as concerns both the consumed energy and the amount of dissipated heat. The performed measurements of the barley malt temperature changes during crushing on two-roller mill were carried out as a part of the overall assessment of the malt grinding problematic.

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