ON THE RHEOLOGICAL PROFILE OF MALT WORT DURING PROCESSING OF SUBSTRATE FOR LAGER BEER

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ABSTRACT

Dynamic viscosity of wort was observed during lager beer base processing. The wort samples were separated in 11 different stages of brewing base preparation. Viscosity was measured by means of rotary viscometer with concentric cylinders geometry. Viscosity gradually increased from 1.75 to 2.1 mPas. Experimental data were mathematically modelled, using Gaussian, exponential, linear, and power law fit. Curve fitting application (MATLAB) was used. The highest correlation (R^2=0.9975) was achieved for Gaussian equation. Obtained dependencies and descriptions represent a powerful tool for predicting wort behavior and designing of brewery technological processes.

INTRODUCTION

Brewing has a long tradition of high standards. The longevity of the process and the fact that the unit stages of brewing have remained essentially unchanged for hundreds of years is documented in number of historical documents. Nevertheless the development of brewing technology is still in progress and improving of beer quality is (apart from other issues) conditioned by studying of physical properties of beer and individual beer components and raw substances.

One of the critical physical properties is viscosity. Concerning breweries and processing laboratories, viscosity is monitored in several different stages of beer production (supplied malt quality tracing, malt and wort quality determination, filtration monitoring, and final product evaluation). Viscosity also plays an important role in theory of filtration. Viscosity is taken into account when designing the filters and setting the working pressures. A high viscosity makes beer filtration more difficult and may lead to starch hazes in the final beer (Lowe et al. 2005).
Beer has an almost ideally viscous behaviour and is therefore a Newtonian liquid (Steffe 1996). This makes it possible to determine the malt, beer, and filtered wort viscosity using relatively simple measuring principles.

This work is focused on measuring of viscosity of wort in different phases of 11° beer base substrate preparation. Wort needs to have various features: first of all, it must contain sugars that the yeast is capable of fermenting into alcohol. These sugars are the energy source that the yeast needs to support its growth. The balance of different types can have a profound effect on the way yeast performs and how efficiently it converts them into alcohol. Moreover, the type of sugar influences the balance of flavour compounds that the yeast produces, and therefore the flavour of the beer (Briggs 2004). Even the hot water treatment is an important factor

MATERIAL AND METHODS

Wort samples

The lager beer (11°) was brewed and its individual components and substrates prepared in the laboratory brewery of Department of Agricultural, Food and Environmental Engineering of Mendel University of Agriculture and Forestry in Brno. The hop Trsice KH 3.14 and Bohemian Pilsner malt was used. The wort samples were separated in different stages of brewing base preparation. Monitored stages are denominated as described in Table 1.

Table 1: Different stages of wort sampling

Sample No.	Time and temperature period of sampling
1	5 min after mashing 52 °C
2	end of 52 °C (after 40 min rest)
3	end of 62 °C (after 30 min rest)
4	end of 65 °C (after 20 min rest)
5	end of 70 °C (after 20 min rest)
6	end of 72 °C (after 20 min rest)
7	end of 78 °C
8	beginning of wort boiling
9	end of 1st wort boiling
10	end of 2nd wort boiling
11	end of wort boiling

The stage 2 (corresponding to sampling procedure) was followed by first enzymatic changes. The stage 6 corresponds to temperature of saccharification. Enzymatic activity (especially activity of amylase) proceeds until reaching this temperature. Conversion of starch to dextrins and monosaccharides depends on holding time at given temperature. Different enzymes are active at different temperatures.

Viscosity measurement

Rheological data were obtained from measurements performed on laboratory Anton Paar DV-3 P Digital Viscometer, which is designed to measure dynamic viscosity, shear stress (τ), and shear rate (γ). The DV-3 P is a rotational viscometer, based on measuring the torque of a spindle rotating in the sample at a given speed. Shear stress is expressed in [$g.cm^{-1}.s^{-2}$], shear rate in [s^{-1}], and viscosity in [mPa.s]. The experiments were performed with use of TR9 spindle. Due to the parallel cylinder geometry, shear stress, except other values, can be determined. Schematic of measuring geometry is shown in Fig. 1.

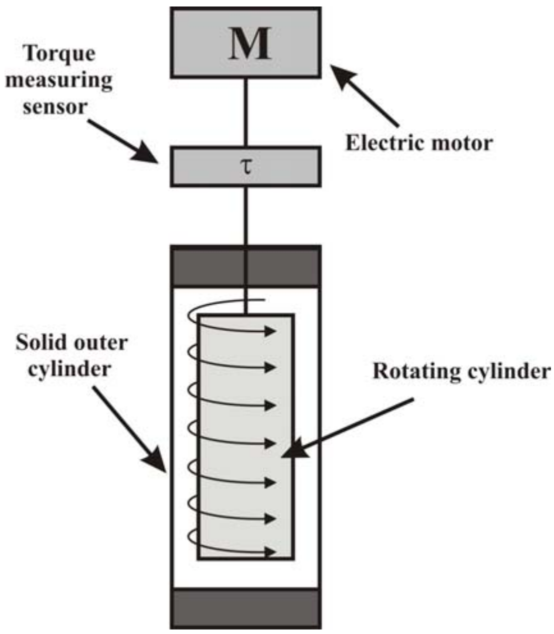

Figure 1
Schematic of measuring principle of rotational viscometer with concentric cylinders geometry

The dynamic viscosity is the viscosity that relates shear stress τ and shear rate γ in a fluid, i.e. $\tau = \eta.\gamma$. The viscous shear stress τ is proportional to the shear rate, the dynamic viscosity η being the proportionality factor. So, thicker materials

have a higher viscosity value causing relatively higher shear stresses at the same shear rate.
The viscosity was determined at share rate of 34 s^{-1}. Measuring was performed at temperature 20°C (similarly as in Lu and Li 2006)

Table 2: Dynamic viscosity of wort at 20°C and shear rate 34 s^{-1}

Sample No	1	2	3	4	5	6	7	8	9	10	11
Viscosity [mPas]	1.75	1.85	1.92	1.94	1.98	2.02	2.04	2.09	2.11	2.10	2.05

There were also other approaches for measuring the wort viscosity, such as quantification of Ostwald viscosity described in Vis and Lorenz (1998), use of falling ball viscometer (Lu and Li 2006, Phiarais 2006) or the system of high throughput autoviscometer - see announcement of Cambridge applied systems AV571 high throughput autoviscometer in *Tribology and Lubrication Technology* (2003) 11:61 (no author name available).
Wort viscosity was modelled using simple mathematical models. Curve fitting application (MATLAB) was used. Following fits were used: exponential, power law, linear, and Gaussian.

RESULTS AND DISCUSSION

Problem of viscosity of beer is discussed in details e.g. in (Hlaváč 2007, Friso and Bolcato 2004, Stewart et al. 1998). Wort viscosity is discussed e.g. in Briggs (2004), who reports wort viscosity values for different brewering technologies in his review tables. Kosař and Procházka (2000) mention that wort viscosity usually ranges from 1.5 to 2.3 mPas. Nielsen and Munck (2003) compared different physical properties of several types of malt and wort and reported viscosity of wort in the range of 1.48 – 2.16 mPas. Higher values are usually connected with increased wort color, changed malt characteristics and other negative impacts on beer nature and malting process economy (Kosař and Procházka 2000). Problematic of high wort viscosity is analysed in Li et al. (2004) or Li, Y., Lu, J. and Gu, G.X (2005).
Another work (Verma et al 2008) correlates wort viscosity (and other indicators) with the properties of hot water extract (HWE). Even the hot water treatment is an important factor influencing wort viscosity (Kottapalli and Wolf-Hall 2008). Wort viscosity, where triticale malts were studied, is also discussed in (Blanchflower and Briggs 2006).

Important factor influencing the substrate viscosity during mashing is α-amylasa. The shorter chains are produced with simultaneously rapidly decreasing molecular weight and consequently decreasing viscosity. The wort viscosity is also largely influenced by β-glucan molecules (Jin et al. 2004). Many wort components contribute to its viscosity, including dextrins, pentosans, and sugars. The increase of viscosity with increasing β–glucan content is not linear but is more nearly a logarithmic relationship and the viscosity contributions of the wort components are not simply additive (Briggs 2004). The β-glucan molecules give very viscous solutions. If they are not broken down in malting or mashing, they are extracted into wort and causing numerous problems to brewer. One of the problems is slowing down the rate at which the wort can be separated from the spent grains and, because it will survive fermentation intact, it will get into beer and greatly reduce rates of beer filtration. As beer is filtered around 0˚C and viscosity increases as temperature is lowered, this is a particular problem. On the other hand, Vis and Lorenz (1998) state that wort viscosity is not a good indicator of β-glucan content. They conclude from the fact that a low β-glucan barley may produce a wort which is not significantly different in viscosity from a high β-glucan barley when mashed under the same conditions. Also both high and low β–glucan barleys produced worts which were significantly different in viscosity when different temperature regimens were used in the mash, and that high β-glucan and low β-glucan malts produced similar worts with different mashing regimens. Influence of enzyme additions and effects is thoroughly discussed in Glatthar et al. (2004) and Phiarais et al (2006).

The problematic of wort separation is rather complicated and is based on an equation developed by Darcy:

$$rate\ \ of\ \ liquid\ \ flow = \frac{pressure\ \times\ bed\ permeability\ \times\ filtration\ \ area}{bed\ \ depth\ \times\ wort\ \ vis\cos ity}$$

Basically, it means that the wort will be recovered more quickly if the vessel used to carry out separation has a large surface area and is shallow (i.e., the distance through the bed is short). Low viscosities (i.e., low β-glucan levels) will help, as will the application of pressure. Thus studying of worth viscosity is a problem of relevant importance.

Table 1 contains the measured values of dynamic viscosity [mPas] of wort in different stages of substrate processing (as described in Materials and methods).

The viscosity value also reflects the level of gum degradation (Li, Y., Lu, J., Gu, G.X., Shi, Z. and Mao, Z. 2005). The viscosity of 12 % wort should range from 1.7 to 2.2 mPas and β-glucan content should not exceed 200 $mg.l^{-1}$ (Kosař and

Procházka 2000), the viscosity of 8 % wort should be around 1.6 mPas (Briggs 2004). The values obtained in presented research are also in general accordance with data reported by Nielsen and Munck (2003). Wort viscosity is also partially affected by following effect. Mashing and wort boiling are connected with transfer of big amount of substances from raw materials and numerous interactions with water ions.

Viscosity of wort (as well as other beer raw products and beer itself) is also decreasing with increasing temperature and decreasing concentration (Severa and Los, 2008). As the temperature is increased, the wort viscosity falls to comparatively low levels and the small particles aggregate and increase in size. Both changes favor faster wort separation. Also malting temperature influences wort viscosity (Igyor et al. 1998).

As it is stated in Blanchflower and Briggs (2006), the viscosities of triticale worts are higher than those of worts from barley malts. In addition, worts from well modified malts are generally turbid. Proteinaceous material (partly degraded prolamins) is the primary cause of this turbidity. Although the degree of malt modification does not influence the rate of wort separation, it has little effect on wort viscosity. High viscosity is caused by pentosans dissolved from the malt during mashing.

Growth of viscosity and produce of ropy wort can be also affected by a gram-positive coccus with the properties typical of pediococci (Hopton and Hall 2008). As the authors state, higher viscosities are attained when the buffering capacity of the medium is increased either by raising the concentrations of the alcoholic extracts or by adding sodium acetate. The material responsible for the viscosity is produced in small amounts only and appeares to be a mucopolysaccharide.

Experimentally determined changes in wort viscosity were modelled by use of several mathematical models. MATLAB software and its Curve fitting toolbox were employed. The highest correlation ($R^2 = 0.9975$) between experiment and model was achieved in case of Gaussian function (denoted as Model 1). Exponential model (Model 2) resulted in satisfactory agreement with correlation coefficient of R^2=0,9668. Less satisfactory results were obtained when using power law model (Model 4) with correlation of $R^2 = 0.9457$ and linear fit (Model 3) with correlation of $R^2 = 0.8352$. Experimental and modelled curves for all computed models are shown in Fig. 2, 3, and 4.

Following function was used for Gaussian fit (R^2=0.9975) – see Fig 2:

f(x) = a1*exp(-((x-b1)/c1)^2) + a2*exp(-((x-b2)/c2)^2) + a3*exp(-((x-b3)/c3)^2)
Coefficients (+ calculation of 95% confidence limit):

a1 = 2.15 (-41.77, 46.07)

b1 = 9.655 (-75.89, 95.2)
c1 = 7.791 (-178.1, 193.7)
a2 = 1.136 (-24.44, 26.71)
b2 = 0.4854 (-36.16, 37.13)
c2 = 4.983 (-57.48, 67.45)
a3 = -0.08876 (-42.24, 42.06)
b3 = 8.58 (-104.1, 121.2)
c3 = 3.221 (-310, 316.5)

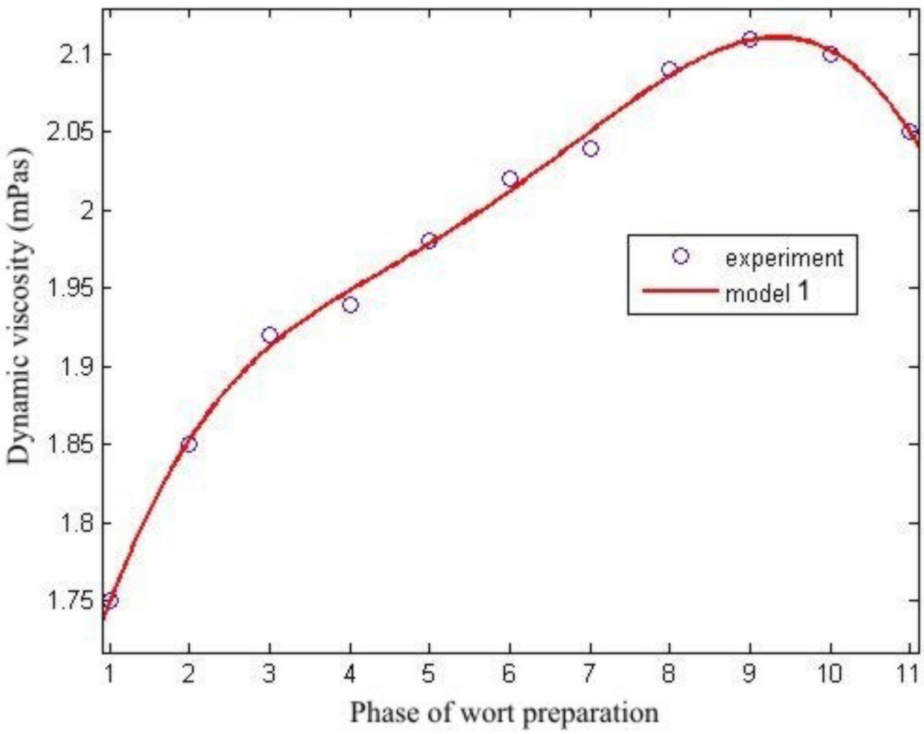

Figure 2
Experimental and modeled data for Gaussian fit

Following function was used for exponential fit (R^2=0.9668) – see Fig.3:

$$f(x) = a*\exp(b*x) + c*\exp(d*x)$$

Coefficients (+ calculation of 95% confidence limit):
a = 9854 (-1.701e+012, 1.701e+012)

b = -0.05289 (-1638, 1637)
c = -9852 (-1.701e+012, 1.701e+012)
d = -0.05291 (-1638, 1638)

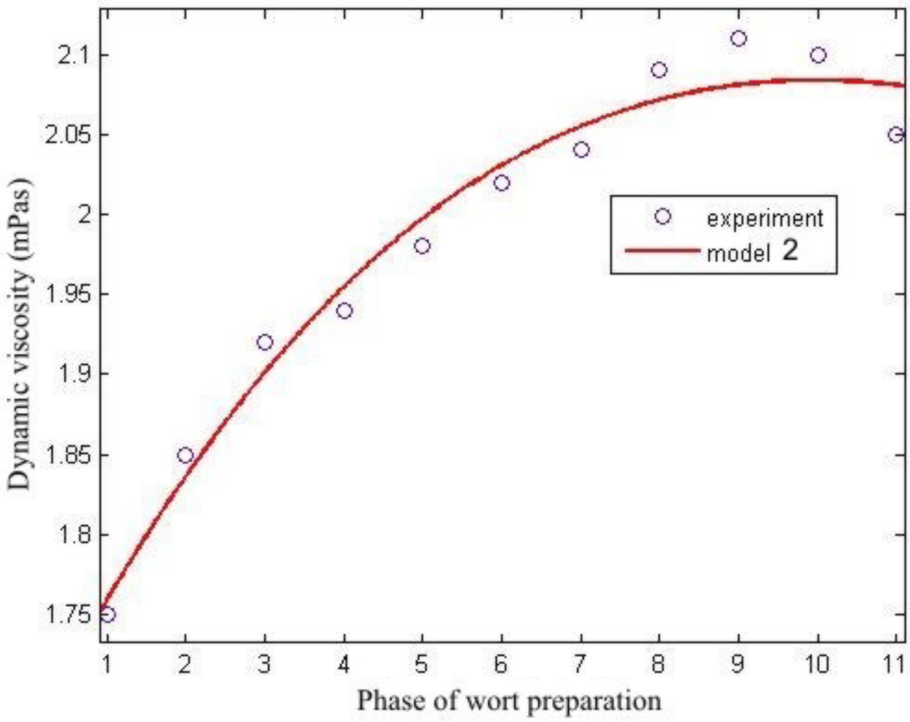

Figure 3
Experimental and modeled data for exponential fit

In the case of linear fit, following function was employed (R^2=0.8352) – see Fig.4:

$$f(x) = p1*x + p2$$

Coefficients (+ calculation of 95% confidence limit):
p1 = 0.03118 (0.02074, 0.04163)
p2 = 1.799 (1.728, 1.87)

For power law fit (R^2=0.9457) – see Fig 4, further mentioned function was used:

$$f(x) = a*x^b+c$$

Coefficients (+ calculation of 95% confidence limit):
a = -2.591 (-21.36, 16.18)
b = -0.06193 (-0.5476, 0.4238)
c = 4.336 (-14.47, 23.14)

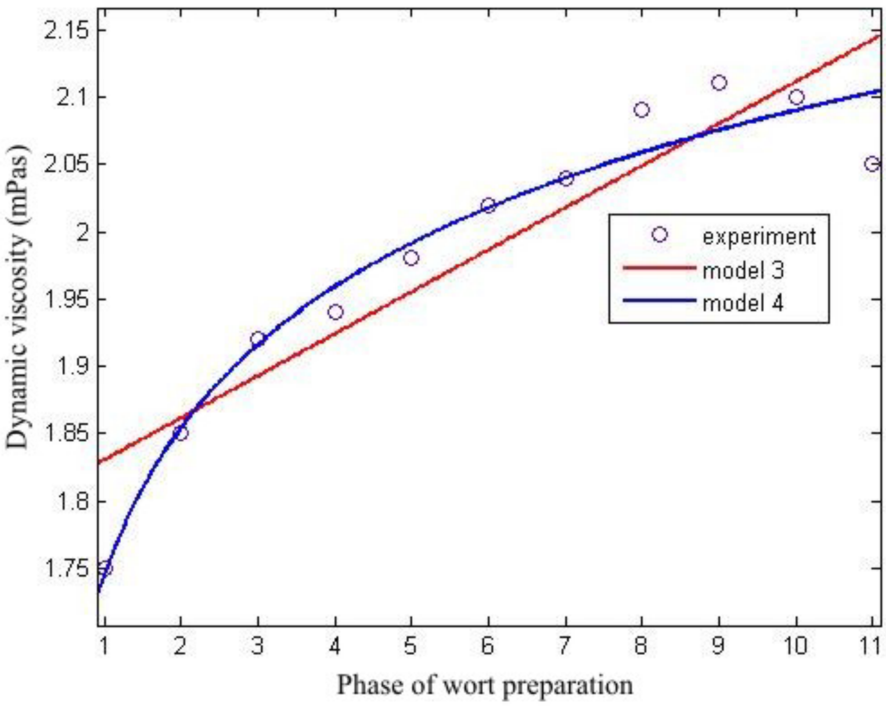

Figure 4.
Experimental and modeled data for linear and power law fit

Modeling of brewery processes is a useful and effective way of detailed insight into specific technological procedures. Such modeling, concerning beer or malt, have been performed e.g. by Dilay et al. (2006), Li et al. (2004) or Phiarais et al. (2006).

CONCLUSIONS

Viscosity of filtered wort, which is acting as a Newtonian fluid, has been monitored during different phases of 11° lager bear base substrate preparation. Viscosity was measured under room temperature and shear rate 34 s^{-1}. Rotary viscometer with parallel cylinders geometry has been used to measure the values of dynamic viscosity. Viscosity values have changed in the range of 1.75 – 2.05 mPas. Measured values are in general accordance with values reported by Kosař and Procházka (2000), Nielsen and Munck (2003), Briggs (2004), and Lu and Li (2006). Changes in viscosity can be explained as an effect of several factors such

as enzymes activity, transfer of big amount of substances from raw materials to wort, and numerous interactions with water ions. There is a general rule that more viscous wort results from the inclusion of a rest (Vis and Lorenz 1998, Wijngaard and Arendt 2006) and more solubilization increase the wort viscosity and retard wort filtration (Lu and Li 2006). The viscosity of wort is also influenced by the macromolecules present. Due to difficulties with beer filtration, low viscosity is a desirable attribute of wort and thus its quantification is important.
Material viscosity during substrate preparation was modeled using several mathematical models. Following fits were used: Gaussian, exponential, linear, and power law with satisfactory correlation coefficients (R^2 = 0.9975, 0.9668, 0.8352, and 0.9457 respectively) between experimental and model data. Curve fitting application (MATLAB) was used. Obtained dependencies and descriptions can serve as a powerful tool for predicting wort behavior and designing of brewery technological processes.

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