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ON THE INFLUENCE OF TEMPERATURE ON DYNAMIC VISCOSITY OF DARK BEER

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Abstract

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Temperature dependence of dark beer dynamic viscosity have been evaluated. The beer samples have been tested in the wide range of temperatures (from 2 to 90 °C) by means of rotary viscometer. The dynamic viscoity ranged from 3.91 to 1.01 mPas. Arrhenius equation have been used to model experimental data with satisfying match $R^2 = 0.993$. Heat gradient in the gap of measuring cell have been described and evaluated.

beer, viscosity, modeling

In the breweries, beer processing laboratories, testing laboraties, etc. viscosity plays an important role in the quality policy. It helps to quantify the quality of the malt and beer raw products, gives insight into filter times and gives an indication of the foam behavior of the finished beer. One of the reasons for this increased importance is the development of high-performance measuring systems which enable a rapid, accurate and fully automatic viscosity determination. Generally speaking, we can define four production areas in which the viscosity is important. First, in the incoming inspection of the malt. Here, viscosity measurement reveals the quality of the malt. Second, in the characterization of the wort quality in the brewhouse. Third, in the filtering process, and fourth, in the finished product. As can be seen, the subject of viscosity is part of the whole brewing process and it has a considerable influence on the product quality.

Beer has an almost ideally viscous behavior and is therefore a Newtonian liquid (Steffe, 1996). This makes it possible to determine the malt and beer viscosity using relatively simple measuring principles.

In this work the viscosities of dark beer were measured as a function of temperature. There have been several studies that have looked at the viscosity – temperature relationship in aqueous sugar solutions, and allow experimentally determined and predicted viscosity by different models to be compared (Kerr and Reid, 1994; Maltini and Anese, 1995; Maltini and Manzocco, 1997). Another work (Hlaváč, 2007) was focused directly on the influence of temperature on viscosity of dark beer.

In this study Arrhenius equation was used to describe experimental data.

MATERIAL AND METHODS

Beer sample

The special dark 12° bottom fermented beer was brewed in the laboratory brewery. The beer was brewed by infusion way with mashing temperature of 52 °C and gradual heating to 62, 65, 70, 72, and 78 °C. The malt with following composition was used: Czech malt 14.4 kg, Bavarian malt 3.1 kg, caramel malt 1.4 kg, and coloured malt 0.6 kg. Drawing-off in the copper was followed by wort boiling with filling of 200 g of hop in 3 doses. The first dose was represented by 50 g of Premiant KH 6.43 hop, the second dose by 100g of Tršice hop, and the third dose by 50g of B+S KH 8.7 hop. The beer wort was flowed to cylindrical-cone tank through countercurrent plate heat exchanger with final temperature of 9 °C. The main fermentation was proceeded at 9 °C (3 days), 6 °C (3 days), and 3 °C (1 day). The post-fermentation was proceeded at 1°C until 38th day.

Viscosity measurement

Dynamic viscosity η [Pas], which is the ratio of shear stress τ [Pa] and share rate $\dot{\gamma}$ [s^{-1}] as shown in Eq. 1

$$\eta = \frac{\tau}{\dot{\gamma}} \, [Pas] \qquad \text{(Eq. 1)}$$

was measured on the digital rotary viscometer Anton Paar DV3-P. Generally, the dynamic viscosity depends on several quantities or variables, such as physical-chemical structure of the sample, temperature, pressure, time, and shear rate. Eqation 1 then can be expressed as

$$\eta(T, p, t, \dot{\gamma}) = \frac{\tau}{\dot{\gamma}} \, [Pas]. \qquad \text{(Eq. 2)}$$

Measuring device of the rotary viscometer was of parallel cylinder geometry. The aparatus was equipped with law viscosity adapter. Usage of this adapter is necessary due to rather law values of measured data. Measuring of dynamic viscosities of law-viscosity fluids with use of other adapters were found to be irrelevant (by measuring defined reference samples).

The temperature of the sample was maintained by connecting the external thermoregulator unit. The viscosity measurements were performed in the wide range of temperatures (2–90 °C). Heating/cooling medium (water) was circulating through the casing of the outer cylinder.

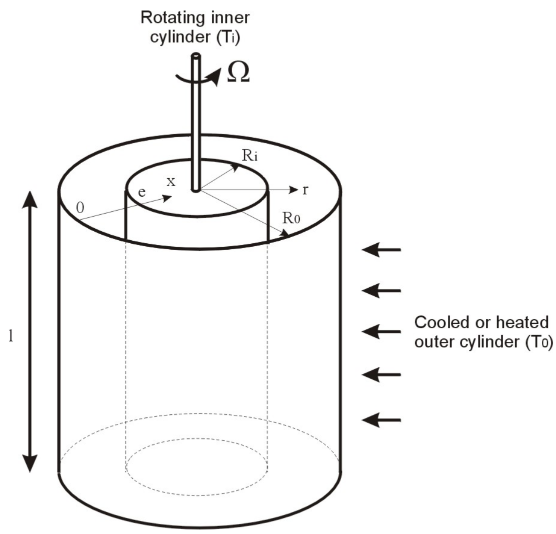
To avoid the influence of temperature gradient in the sample, the temperature was changed (and measurement performed) in following manner. The sample was exhibited to the effect of the temperature-controlled media for 3 minutes (between individual temperature steps). According to undermentioned relations and theory of temperature gradient in the gap, this time is sufficient for achievement a temperature steady state in the sample as well as the measuring cell elements.

Arrhenius model (Steffe, 1996) was used to study the temperature dependence of viscosity.

RESULTS AND DISCUSSION

Determination of the temperature gradient in the gap

For the measurments performed under different temperatures (with constant change of the temperature), the influence of measuring cell geometry on the temperature gradient through the gap should be considered. Similar problem (for starch-based food products) was solved in Lagarique et al. (2007). Theoretically, the objective is to predict, from the outer cylinder temperature (T_0), the temperature gradient through the gap as well as the inner cylinder temperature (T_i) when the outer cylinder is heated or cooled while the inner cylinder is moving and torque recorded (see Fig. 1). Both the inner and the outer cylinders are metallic and thus these parts are much better conductors than the fluid flowing in the gap. Since heat transfer by radiation can reasonably be neglected, the problem is then linear.



1: *Schematic of the measuring geometry*

The fluid temperature at a position x in the gap and at time t, T(x,t), can be deduced from the unit-step response F(x,t), which would be the temperature at this point if the outer cylinder temperature was sharply raised from 0 to 1 °C.

$$T(x, t) = \int_0^{\infty} E(x, t')T_0(t - t')dt' \text{ with } E(x, t) = \frac{\partial F(x, t)}{\partial t}. \qquad \text{(Eq. 3)}$$

If the gap thickness (e) is much lower than the diameter of cup and bob, curvature and end effects can be neglected.

A simplified approach consists in establishing a heat balance in the gap divided in two equal parts. Half of the fluid is considered to be at the same temperature as the inner cylinder and the other half at the temperature of the outer cylinder. The internal energy variation of the inner cylinder and half of the fluid is then equal to the heat flux through the gap. The heat flux is estimated, as for steady state, by the temperature difference between the outer and the inner cylinders divided by the resistance by conduction in the gap:

$$\left(\frac{m_m c_{pm}}{A_m} + \frac{1}{2}\rho c_p e\right) \frac{dT_i}{d_t} = \frac{(T_0 - T_i)}{e/\lambda}, \qquad \text{(Eq. 4)}$$

where λ, ρ and c_p are, respectively, the fluid thermal conductivity, density and specific heat, and m_m, c_{pm} and A_m are, respectively, the inner cylinder mass, specific heat and vertical surface.

By using this approach, the unit-step response of the inner cylinder temperature is

$$F(x = e,t) \approx 1 - \exp\left(-\frac{t}{\tau}\right) \quad \text{with } \tau = \frac{m_m c_{pm}/A_m + \rho c_p e/2}{\lambda/e}. \qquad \text{(Eq. 5)}$$

Moreover, the temperature profile between the outer and the inner cylinders will be assumed linear. Eq. 5 is also reported by several authors (Rohsenow, Hartnett, & Ganic; 1973). Comparable unit step response could be obtained from classical analytical solutions of heat transfer between infinite plates (Carslaw & Jaeger, 1959).

In particular, for a linear increase in temperature characterised by a heating rate, dT/dt, the inner cylinder temperature follows a first order ramp response. After a transient phase, the inner cylinder temperature has the same evolution as the outer cylinder temperature (same heating rate) but with delay equal to the time response of the system τ. The temperature difference in the gap is then equal to (dT/dt) τ.

Influence of temperature on dynamic viscosity

The values of dark beer dynamic viscosity [mPas] measured under different temperatures [°C] at share rate of 34 s^{-1} are listed in Table I. The values of beer viscosity referred in literature (Hlaváč, 2007; Friso and Bolcato, 2004) are slightly lower, because of different beer samples used (lager beer instead of dark beer).

I: *Dynamic viscosity values measured under different temperatures*

Temperature [°C]	2	5	7.5	10	12.5	15	20	25	30	35	40	45	50	65	80	90
Viscosity [mPas]	3.91	3.61	3.36	3.17	3.02	2.81	2.53	2.21	2.01	1.9	1.73	1.57	1.47	1.25	1.1	1.01

Dynamic viscosity of dark beer is influenced by many factors. If we consider that beer acts as Newtonian fluid (Stefe, 1996), the important role, beside temperature, which will be discussed below in details, has the chemical composition, volume ratio of beer components and other factors. The correlation of selected beer components with beer and malt viscosity was commented e.g. in (Li et al., 2004; Jin et al. 2004).

Influence of temperature on beer dynamic viscosity was modeled. Modeling provides a means of representing a certain quantity of rheological data in terms of a simple mathematical expression. Many forms of the equations are possible and one master model, suitable for all situations, does not exist (Steffe, 1996). The influence of temperature on the viscosity of Newtonian fluids can be expressed in terms of an Arrhenius type equation involving the absolute temperature (T), the universal gas constant (R), and the energy of activation for viscosity (E_a):

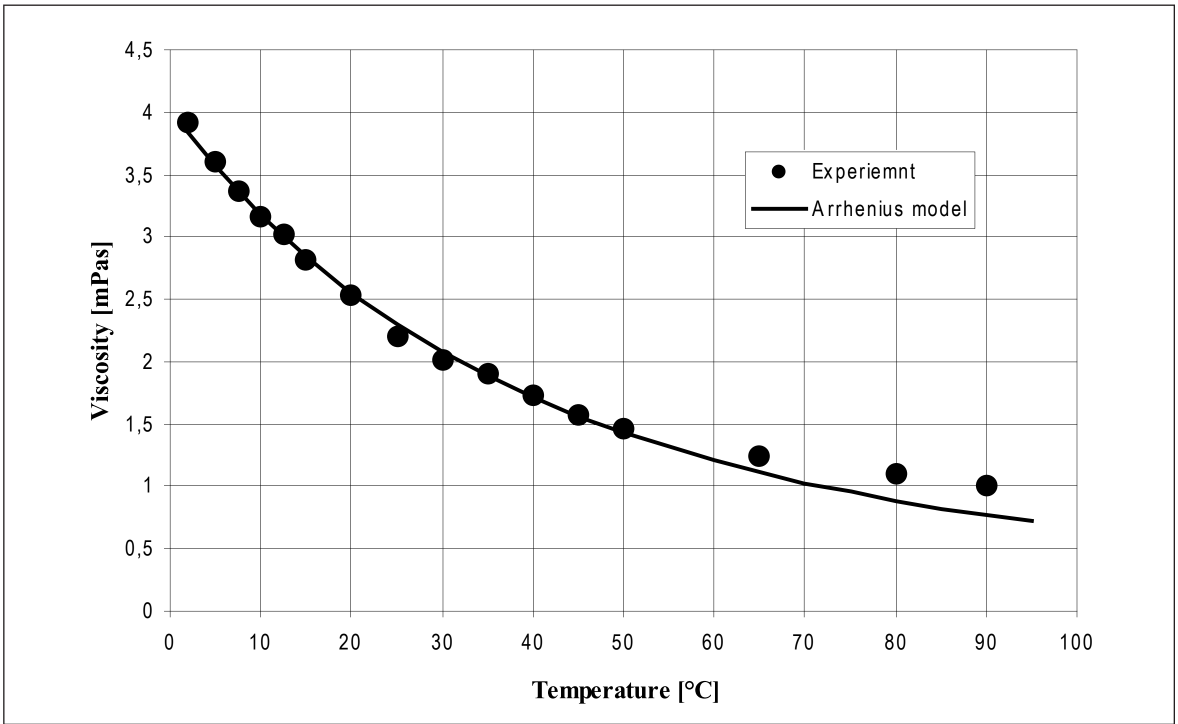
$$\mu = f(T) = A \exp\left(\frac{E_a}{RT}\right). \qquad \text{(Eq. 6)}$$

E_a and A are determined from experimental data. Higher E_a values indicate a more rapid change in viscosity with temperature. Considering an unknown viscosity (μ) at any temperature (T) and a reference viscosity (μ_r) at a reference temperature (T_r), the constant (A) may be eliminated and the resulting equation written in logarithmic form:

$$\ln\left(\frac{\mu}{\mu_r}\right) = \left(\frac{E_a}{R}\right) - \left(\frac{1}{T} - \frac{1}{T_r}\right). \qquad \text{(Eq. 7)}$$

Figure 2 shows the plot of experimental and computed data of the viscosity-temperature dependace. Arrhenius model exhibited satisfying agreement with experiement and $R^2 = 0.993$. The value of activating energy has been set as $E_a = 14902$ and A = 0.0031.

Generally, the behavior of beer can be successfully compared with other similar Newtonian fluids. For example, the viscosity models, activation energies, and processing properties described in (Nindo et al., 2004) for fruit juices are well applicable for beer as well. Above stated beer characteristics can be used for describing many processes and performing many operations, such as modeling, simulation and optimization of beer technologies. Example of practical use of such data is included in (Dilay et al., 2005).



2: *Experimental and modeled dependance of beer viscosity on temperature*

SOUHRN

Vliv teploty na dynamickou viskozitu černého piva

Byla sledována dynamická viskozita přesně definovaného černého piva při různých teplotách. Pivo bylo považováno za newtonovskou kapalinu. Viskozita měřená při teplotách od 2 do 90 °C se pohybovala v rozsahu 1,01 až 3,91 mPas. Pro měření reologických hodnot byl použit digitální rotační viskozimetr s geometrií měřící komory válec – válec. Zjištěná experimentální závislost byla modelována pomocí Arrheniova vztahu. Bylo dosaženo velmi uspokojující shody experimentu s modelem R^2 = 0,993. Popsán a hodnocen byl též teplotní gradient v meziprostoru mezi válci měřicí komůrky.

pivo, viskozita, modelování

SUMMARY

Viscosity of dark beer, which is acting as a Newtonian fluid, has been monitored under different temperatures. Viscosity measured in the range 2–90 °C changed from 3.91 to 1.01 mPas. Rotary viscometer with parallel cylinders geometry has been used to measure the values of dynamic viscosity. Documented values are in general accordance with literature data (Friso, 2004). Arrhenius type equation has been used to model measured data and satisfying accordance R^2 = 0.993 has been found. Perfomed analysis results in validation of Arrhenius model as a powerfull tool for describing a viscosity-temperature dependance of dark beer. Parallel cylinder measuring geometry has been evaluated in temrs of heat gradient in the gap of measuring cell. Theoretical description of temperature difference in the gap (with delay equal to the time response of the system τ) has been developed and found to be equal to (dT/dt) τ.

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