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Influence of temperature on the filter cake resistance in a lauter tun

High temperatures are maintained in a lauter tun to reduce the filtration time. The temperature affects the flow rate through the changing viscosity. In addition, the sedimentation behaviour of the particles also depends on the temperature. Changes in the settling velocity are assumed to affect the filter cake resistance and thus the flow rate. The influence of temperature (range: 40–78 °C) on cake formation was investigated. Calculations of the settling velocity revealed a higher settling rate at higher temperatures due to a reduction in the density and viscosity of the liquid. The effect was confirmed for larger particles by performing a sedimentation test, but smaller particles were hindered from settling at higher temperatures. Fine particles remained in suspension because of thermal convection, providing buoyancy to counteract the gravitational sedimentation. The hindered particle settling explained the lower filter cake resistance at high temperatures and thus the higher flow rate.

Descriptors: filter cake resistance, lautering, sedimentation, temperature, viscosity

1 Introduction

Mash separation is one of the most important solid-liquid separation process in beer production and a time-critical step in the brewhouse [19]. A lauter tun is often used to separate the mash into its solid (spent grains) and liquid (wort) phase. To ensure a short and efficient processing time in the lauter tun, a high flow rate must be achieved. The filtered volume (*V*) per unit time (*t*) depends on the filter area (*A*), differential pressure (*Δp*), and cake height (*h*) according to

$$\frac{v}{t} = \frac{A \cdot \Delta\rho}{h \cdot \eta \cdot \alpha_h} \ . \qquad \text{(Eq. 1)}$$

A high flow rate requires a low viscosity (η) of the wort and a low filter cake resistance (α_h). These characteristics strongly depend on the quality of the raw materials (e.g., cytolytic modification) [8, 9, 11, 13, 14]. A low viscosity can also be achieved through high temperatures despite the malt quality; hence, lautering is usually conducted at temperatures of up to 78 °C [1, 4, 11, 18]. However, the filtration time does not always correlate with the wort viscosity as summarized by *Greffin* and *Krauß* [11]. In addition, *Barrett* et al. [2] showed that the viscosity has only a minor influence on the flow rate compared with the physical blocking of the cake. Therefore, it can be concluded that the reduced viscosity is not the only reason for the higher flow rate at high temperatures. This is supported by *Bühler* et al. [3, 5] who showed that changes in the filterability at different temperatures are not caused by the viscosity; instead, a reduction in the filter cake resistance at higher temperatures is responsible. The influence of temperature on the filter cake resistance is investigated in this work. In contrast to earlier studies [3, 5, 13], this paper does not aim to analyse the temperature-dependent structural changes of the particles that alter the resistance; these particle agglomeration effects were kept constant. It is investigated in this paper how the temperature affects the resistance based on differences in the sedimentation behaviour of the particles.

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The settling velocity (w_f) of particles depends on the viscosity and density (ρ_f) of the liquid, and the gravitational field strength (g), particle density (ρ_s) and size (d), according to

$$w_f = \frac{\rho_s - \rho_f}{18 \cdot \eta} \cdot g \cdot d^2 \ . \qquad \text{(Eq. 2)}$$

Both the viscosity and density are temperature dependent. The dependence of the settling velocity on the particle size and density, in combination with the sedimentation rest [15] and the broad size distribution of particles in the mash [20], results in the formation of a multilayered filter cake. Fine particles (< 500 µm) settle later than larger particles (> 500 µm, e. g., husks) to form a top layer on the compressible bottom layer [7, 12]. This top layer has a high filter cake resistance compared with the bottom layer [2, 13, 14]. The cake layer formation can be divided into three steps (Fig. 1). First, the mash is transferred to the lauter tun (t_1). The particles immediately begin to settle on the filter medium (false bottom) with larger and denser particles sinking faster than smaller ones [15]. After the sedimentation rest (t_2), most of the smaller and less dense particles previously present in the lower regions have been displaced by the coarser particles that form the bottom layer. Some small particles do not settle at all unless the liquid level is decreased during filtration and their buoyancy ceases to exist (t_3). The

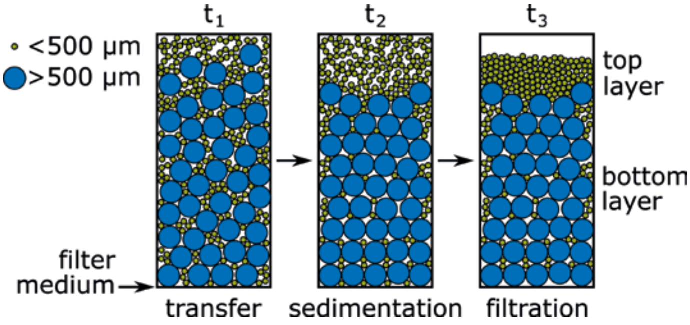

Fig. 1 **Schematic illustration of the distribution of small (< 500 µm) and large (> 500 µm) particles in the filter cake after the mash transfer (t_1), sedimentation rest (t_2), and filtration process (t_3). Compressibility of the bottom layer is neglected in the scheme**

concentration of fine particles in the vicinity of the filter medium is reduced by trub wort pumping at the beginning of the filtration step. Most of the fine particles settled on top of the bottom layer by the end of the filtration, resulting in the characteristic layering of the lauter tun filter cake [7, 12]. The migration of the top layer particles into the bottom layer can be neglected during the filtration when there is no raking [7].

The sedimentation behaviour of the fine particles is expected to be influenced by temperature to a higher degree than the larger particles because of the low size and density. It is therefore assumed that the temperature specifically influences the formation, and thus the resistance, of the filtration-critical top layer. Consequently, the temperature dependence of the top layer has a major effect on the flow rate, in addition to a minor effect of the viscosity.

Herein, the influence of temperature (range: 40 – 78 °C) on the flow rate in the lauter tun is investigated using a lab-scale filtration device. In addition to the practical filtration temperature of 78 °C, lower temperatures are examined to understand temperature-dependent differences in the filtration process.

2 Materials and Methods

2.1 Mashing procedure and filtration test

Malt was ground in a DLFU disk mill (Bühler AG, Uzwil, Switzerland) with a grinding gap of 0.65 mm. Grist (500 g) and distilled water at 62 °C were mixed in a ratio of 1 : 3.5 and stirred on a heating plate at 65 °C for 1 h. The temperature was then increased to 78 °C (maximum temperature to avoid denaturation of enzymes) for each experiment to ensure constant conditions with regard to particle agglomeration [5, 13]. Afterwards, the mash was adjusted to a final mass of 2350 g (solid-liquid ratio: 1 : 4.7) and cooled to the required temperatures for the further tests using a water bath.

A lab-scale lauter tun (diameter: 10 cm, liquid level: ~29 cm) equipped with a false bottom and heating jacket was used for the filtration tests at different temperatures (40, 50, 60, 68, 71, 73, 75, 76, 77, and 78 °C). In addition to the practical lautering temperature of 78 °C, lower temperatures were tested to investigate the influence of temperature on the filtration process and particle settling. No temperatures higher than 78 °C were applied to avoid particle agglomeration as described in the literature [5, 13]. 100 mL of water was added to the false bottom to exclude trapped air. After a 5 min sedimentation rest, an iPump1Q peristaltic pump (Baoding Signal Fluid Technology Co., Ltd., Baoding, China) was used to recirculate the trub wort at a flow rate of 28 g/min for 5 min. The flow rate was then increased to 118 g/min and the filtrate mass was recorded over time using a scale until at least 1200 g of the filtrate had been filtered. This enabled the detection of a decrease in the flow rate due to a blocking of the cake. Only first wort was filtered without washing the cake and no raking knives were used to preserve the structure of the cake. The cake height was measured using a folding rule.

2.2 Determination of particle and wort characteristics

The characteristics of the mash particles (particle size distribution, density) and wort (density, viscosity) were determined at different temperatures for use in subsequent calculations. The particle size distribution of the entire mash (Fig. 2) was determined using

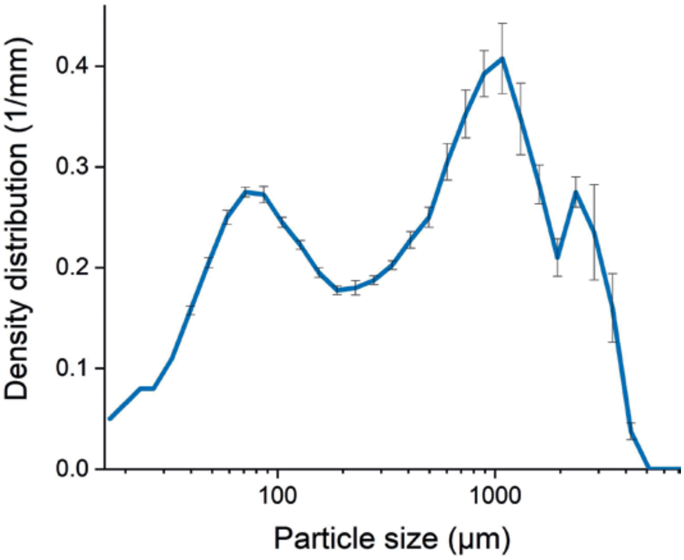

Fig. 2 **Particle size distribution of the mash (n = 4, logarithmic scale)**

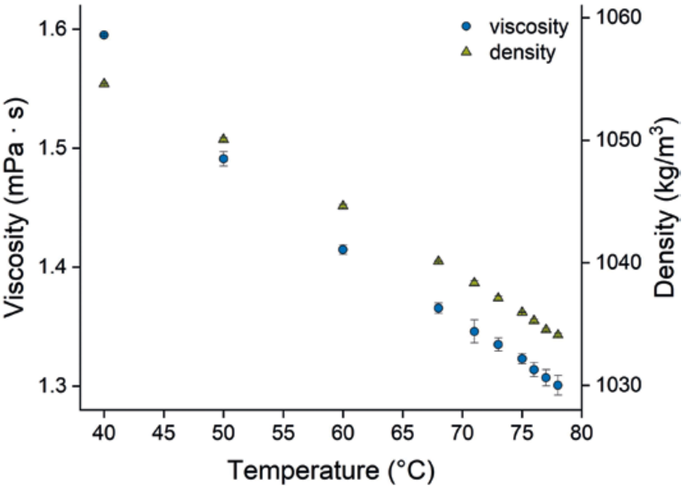

Fig. 3 **Viscosity and density of wort at different temperatures (n = 3)**

a QICPIC particle size analyser (Sympatec GmbH, Clausthal-Zellerfeld, Germany).

Fine particles were isolated from the mash by wet sieving (mesh size: 500 µm) using distilled water in a similar way to that in the literature [13]. The particle size distribution of the fine particles was determined using a Mastersizer 3000 (Malvern Panalytical GmbH, Kassel, Germany), which gives a higher resolution at small sizes compared with the QICPIC. The density of the wort (Fig. 3) and filter cake particles was determined using a pycnometer at different temperatures. Different particle densities were found for the top layer (1432 ± 6 kg/m^3) and bottom layer particles (1517 ± 19 kg/m^3). The wort viscosity at different temperatures (Fig. 3) was determined using an AR-G2 rheometer (TA Instruments Ltd., New Castle, USA) at the constant shear rate of 192 s^{-1} corresponding to the shear rate in the filtrate pipe in the filtration test.

2.3 Calculation of settling velocity

The settling velocity was determined as an example for particle sizes within the mash (125, 250, 500, 1000, 2000, and 4000 µm) at different temperatures. A general form of equation 2 was used to consider differences in the Reynolds numbers (*Re*) for different particle sizes:

$$w_f = Re \cdot \frac{\eta}{d \cdot \rho_f} \; . \qquad \text{(Eq. 3)}$$

The calculation considered the density of the particles, which was assumed to be independent of temperature, and the density and viscosity of the liquid at different temperatures were considered. Different shape factors for fine (rounded: 0.81) and bottom layer particles (elongated: 0.61) were assumed [6]. The settling velocity was corrected by multiplying with a concentration factor (β) [17]:

$$\beta = (1 - C)^{\alpha(Re)} \; , \qquad \text{(Eq. 4)}$$

which includes the volumetric concentration (C) of the mash and an exponential factor (α) with dependence on the Reynolds number.

2.4 Sedimentation test

Two different sedimentation tests were conducted to verify the calculated settling velocities of the mash particles at different temperatures. Firstly, the entire mash was used to analyse the sediment height of the fine and bottom layers over time (large-scale test). Secondly, the sedimentation behaviour of a suspension consisting only of isolated fine particles (without the influence of coarse particles) was investigated (small-scale test). The mash was transferred to a graduated cylinder (700 mL, height: ~25 cm) with a similar liquid height to that during the filtration for the large-scale test. The cylinder was kept at the required temperatures using a transparent water bath that allowed the measurement of the heights of the layers. The height was measured after 5 and 10 min of sedimentation rest to determine the temperature-dependent differences in the settling of smaller and larger particles. The fine particles did not settle at all due to particle movement at higher temperatures. Therefore, the maximum height of the particles in the suspension was considered as the sediment height (as illustrated in Fig. 1, t_2).

A modified small-scale test was used to analyse the sedimentation behaviour of only the fine particles that remained in suspension in the large-scale test. Isolated fine particles (5.7 g) were suspended in 200 mL of wort to give a particle concentration corresponding to that of the supernatant in the filtration tests. The suspension was transferred to a graduated cylinder (height: ~11 cm). The particles in the supernatant and in the sediment were removed from defined heights (3.7 and 0.5 cm, respectively) after 10-min sedimentation rest using the peristaltic pump. The volume-weighted mean size of these particles (*D[4,3]*) was measured to serve as an indicator of the buoyancy. A reference measurement using distilled water instead of wort was performed at 40 and 78 °C for the supernatant.

2.5 Calculation of filter cake resistance

The filter cake resistance after particle sedimentation (t_2) was estimated for the fine and bottom layers from

$$\alpha_h = 180 \cdot \frac{(1 - \varepsilon)^2}{d^2 \cdot \varepsilon^2} \; . \qquad \text{(Eq. 5)}$$

The median values of the size distributions of fine particles (60 ± 5 µm) and the entire mash (1665 ± 125 µm) were used as the particle sizes for the fine and bottom layers, respectively. The porosity (ε) was determined from

$$\varepsilon = \frac{v_{total} - v_{particle}}{v_{total}} \qquad \text{(Eq. 6)}$$

using the total sediment volume (V_{total}) determined by the height measurement in the large-scale sedimentation test. The volume of the particles ($V_{particle}$) was determined by dividing the gravimetrically determined mass of each layer by its corresponding particle density.

2.6 Statistics

Each experiment was performed three times (n = 3) unless stated otherwise. Means and standard deviations were calculated, and a statistical evaluation was conducted using OriginPro 2019b (OriginLab Corporation, Northampton, USA). Significant differences between the means were determined using a t-test.

3. Results and Discussion

A filtration test was used to investigate the influence of temperature on the flow rate. A characteristic turning point in the flow rate was observed for each temperature (examples in Fig. 4a) after around 10 min. This drop in the flow rate is based on the high resistance of the fine particle layer causing blocking and thus a compression of the bottom layer of the cake as described in the literature [14].

The average flow rate before and after the turning point was calculated to evaluate the temperature dependence (Fig. 4b). Before the turning point, the flow rate increases only slightly with increasing temperature. After the turning point, the flow rate increases more for temperatures > 60 °C. Therefore, the flow rate after blocking is influenced by the temperature to a higher degree than before blocking. It can be concluded that the top layer has a greater temperature dependence than the bottom layer as the

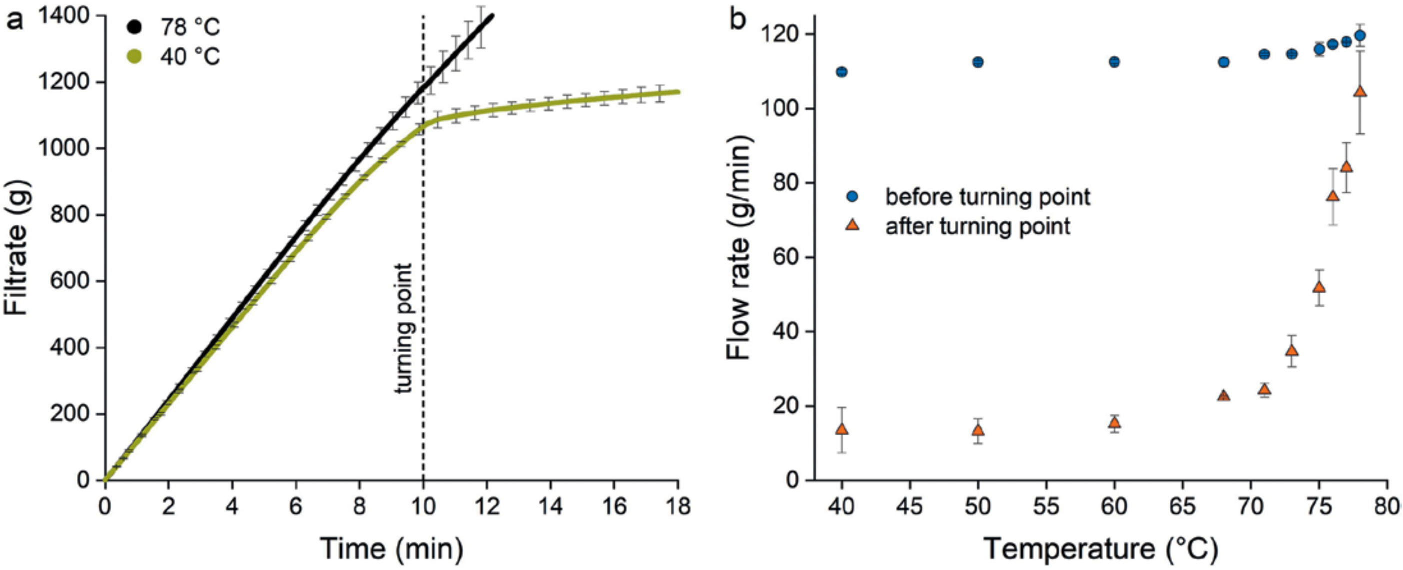

Fig. 4 (a) Filtrate mass per time at 40 and 78 °C. Vertical line indicates the turning point after the filter cake blocking at around 10 min. (b) Average flow rate before and after the turning point at different temperatures (n = 3)

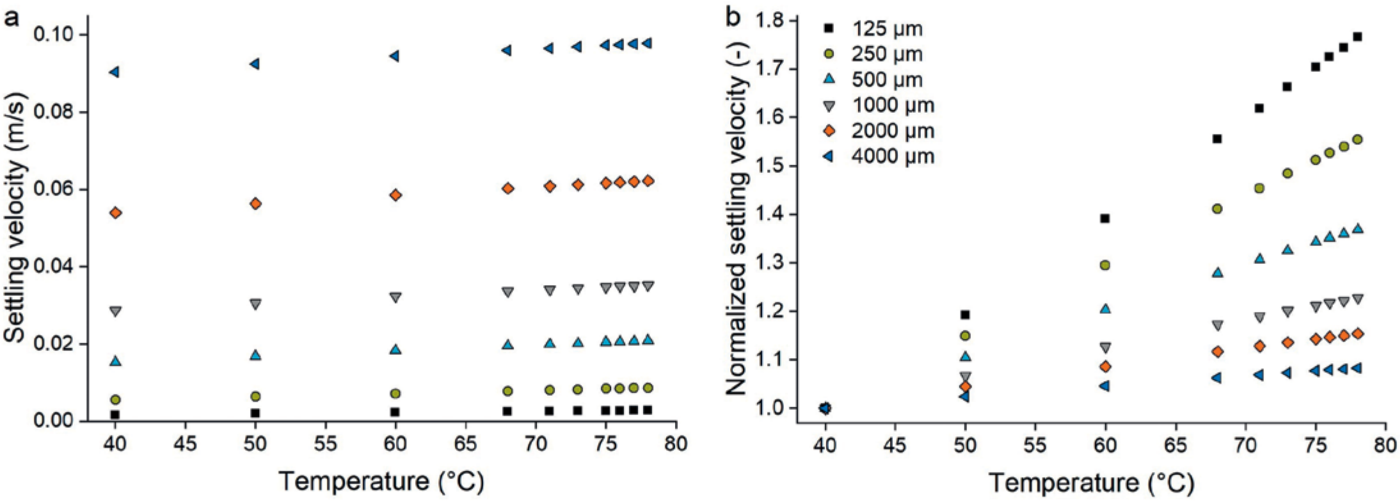

Fig. 5 (a) Calculated settling velocity for various particle sizes at different temperatures and (b) the data normalized to the value at 40 °C

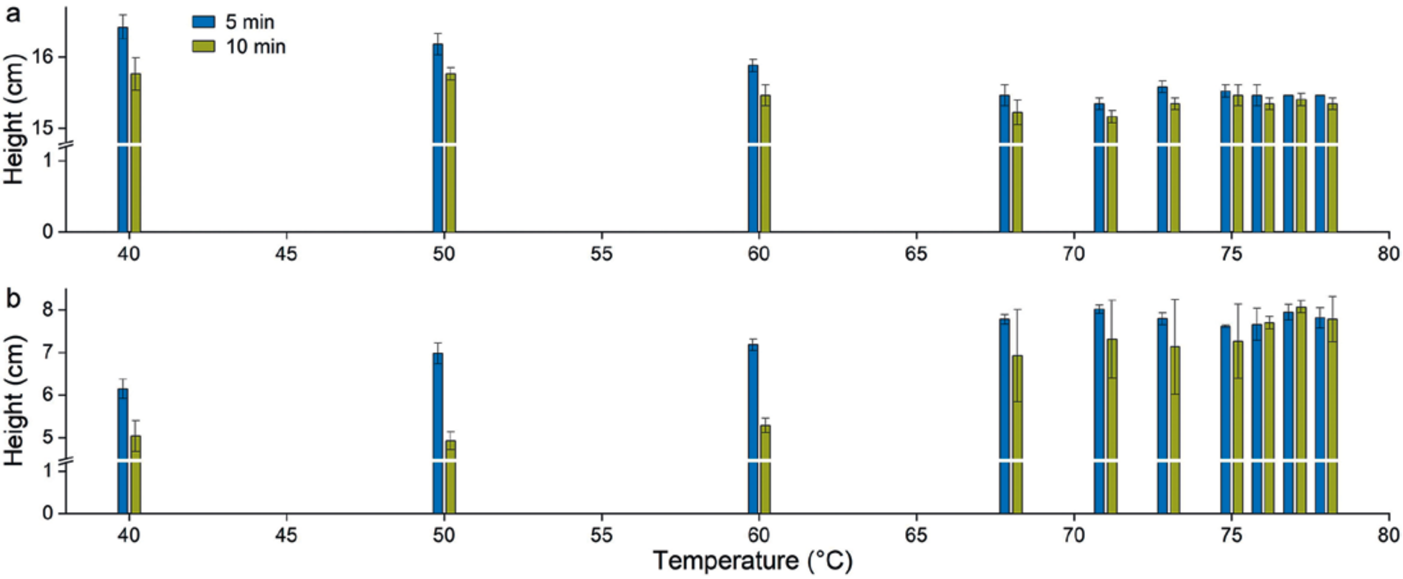

Fig. 6 Sediment height after 5 and 10 min at different temperatures (n = 3) of (a) the bottom layer and (b) the fine particle layer (break in y-axis)

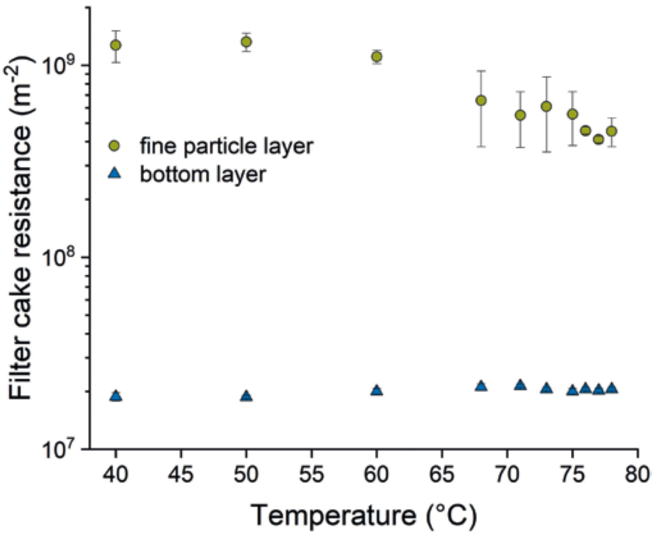

Fig. 7 Filter cake resistance of the fine particle and bottom layers after sedimentation (10 min) at different temperatures (logarithmic scale, n = 3)

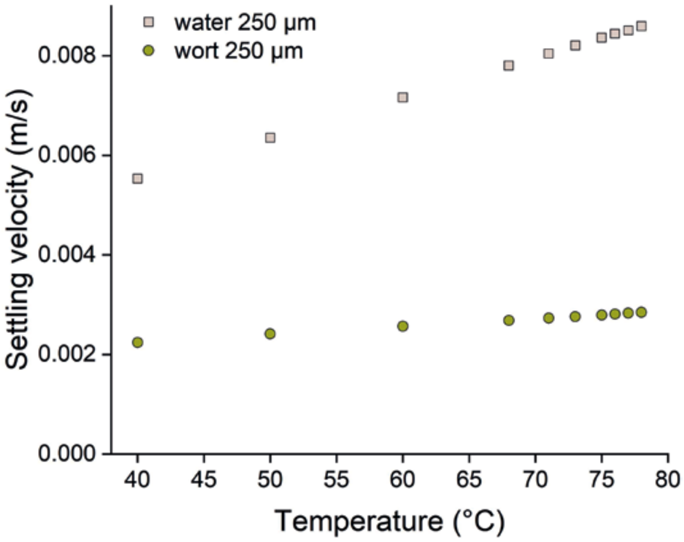

Fig. 9 Calculated settling velocities of particles with a size of 250 µm in water and wort at different temperatures

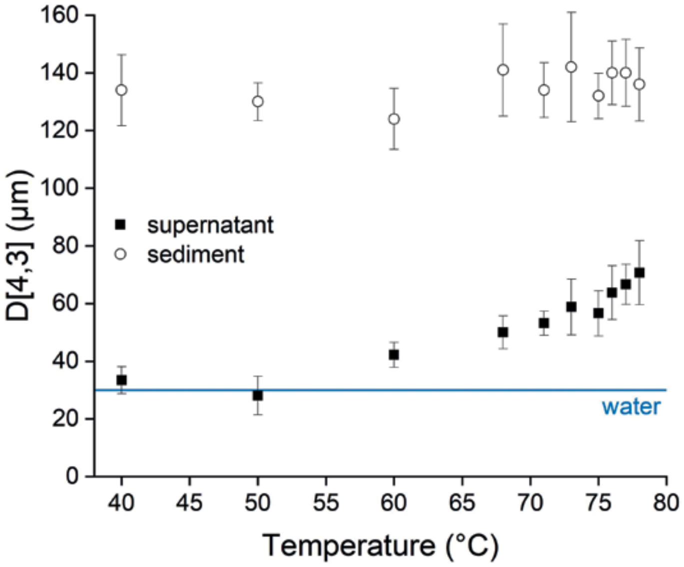

Fig. 8 Mean particle size (D[4,3]) of the supernatant (buoyancy indicator) and sediment in the fine particle sedimentation test after 10 min at different temperatures (n = 30). Horizontal line indicates the mean particle size in the supernatant when using water instead of wort

blocking is caused by the high resistance of the fine particle layer [14]. In addition, a higher correlation between viscosity and flow rate before blocking ($R = -0.85$, $p < 0.01$) than after blocking ($R = -0.69$, $p < 0.05$) was found. Therefore, the viscosity has a minor impact after the blocking.

An influence of temperature on the sedimentation behaviour of the different mash particles was expected according to equation 2 as the density is reduced at higher temperatures as well as the viscosity (Fig. 3). Therefore, the settling velocity for different particle sizes at different temperatures was calculated (Fig. 5a).

The larger the particle size, the higher the calculated settling velocity. In addition, the settling velocity increases with higher temperatures. When normalizing the settling velocity to 40 °C (Fig. 5b), it can be seen that the temperature dependence is stronger for smaller particle sizes. Therefore, it was expected that the sedimentation behaviour of the particles, and thus the structure of the top and bottom layers, differs with temperature. This was investigated by measuring the sediment height of the different layers at different temperatures and after different settling times (Fig. 6).

There is no difference in the height after 10 min over the range between 40 and 78 °C for the bottom layer (Fig. 6a), which means that sedimentation of the bottom layer is finished after 10 min at the latest regardless of the temperature. A significant difference in the sediment height between 5 and 10 min was observed at low temperatures but was reduced as the temperature increased. This confirms the higher settling velocity at higher temperatures as the final sediment height is reached faster at higher temperatures.

The sedimentation test of the fine particle layer showed a different behaviour (Fig. 6b). There is again a significant difference between the 5- and 10-min sedimentation time at 40 °C but not at 78 °C. However, the height of the fine particles in suspension (see Fig. 1, t_2) between 40 and 78 °C still differs after 10 min. Instead of a lower height, as would have been expected due to the higher settling rate of fine particles (Fig. 5), a greater height was found at higher temperature. This means that some of the fine particles do not settle at all at temperatures > 60 °C and remain in suspension. This trend agrees with the flow rate after blocking (Fig. 4b) which increases above this temperature and is a hint that the flow rate depends also on the settling behaviour of the fines.

The porosity of the top layer is increased due to the lower particle packing density when the fine particles do not sediment at higher temperatures. Consequently, the calculated filter cake resistance (at t_2) of the fine particle layer is reduced by 64 % at 78 °C compared with that at 40 °C (Fig. 7). A high correlation ($R = -0.74$, $p < 0.05$) of the resistance of the fine layer with the flow rate after blocking was found, which confirms the dependence of the flow rate on the fine particles.

The resistance of the top layer is about 22 times higher than that of the bottom layer at 78 °C, which is in agreement with the literature [3, 13]. There is no significant difference in the resistance of the bottom layer between 40 and 78 °C meaning that the formation of this layer is not affected by temperature. However, the resistance of the bottom layer can increase during filtration based on compression [14] which was not considered in the calculation.

The decrease in the resistance of the fine layer at higher temperatures results in a lower degree of cake compression. This was verified by measuring the cake height as indicator for the compression. The cake height was 10.8 cm (± 0.2) at 78 °C and 7.97 cm (± 0.05) at 40 °C (compared with the initial cake height of 15.2 ± 0.2 cm prior to the filtration).

The lower resistance of the fine particle layer at increasing temperature could be explained by thermal convection leading to a buoyancy effect that counteracts the particle sedimentation and results in lower particle packing. The mean particle size of the supernatant (buoyancy indicator) was measured to quantify the particles in suspension that did not settle (Fig. 8). The mean particle size of the supernatant increases with increasing temperature meaning that larger particles are held in suspension at higher concentrations. In contrast, there is no significant difference in the particle size of the sediment between 40 and 78 °C, which has a higher particle size in general. This shows that the smaller particles in the top layer are especially affected by buoyancy.

There is a high correlation of the buoyancy indicator with temperature ($R = 0.93$, $p < 0.001$). In addition, a high correlation of the buoyancy indicator with the filter cake resistance ($R = -0.95$, $p < 0.001$) and flow rate ($R = 0.87$, $p < 0.01$) after blocking were found. Therefore, the hindered sedimentation of the fine particles at high temperature is responsible for the lower resistance in this layer, causing the increase in the flow rate.

A control experiment showed that the buoyancy effect at higher temperatures is only present when using wort. The effect was not observed when the particles were suspended in water (Fig. 8, horizontal line) where the mean particle size at 40 °C (31 ± 3 µm) and 78 °C (30 ± 12 µm) did not differ significantly from the value with wort at 40 °C. Therefore, the buoyancy effect that counteracts sedimentation at high temperatures is only present when suspending the particles in wort. This is due to the higher viscosity and density of wort resulting in a lower settling velocity compared with water (Fig. 9, example calculation using a particle size of 250 µm). In this case, the more pronounced buoyancy counteracts the particle sedimentation in wort even when the settling velocity increases at higher temperature. The higher settling rate due to the lower viscosity and density is more pronounced than the buoyancy when suspending the particles in water. Thus, the particles settle in water even at higher temperatures.

The dependence of the buoyancy effect on the viscosity and density of the liquid shows that it can be affected by the characteristics of the wort and malt. For example, a higher wort gravity results in a higher density and viscosity, which favours the buoyancy at high temperature. An increase in viscosity due to poor cytolytic modification could also increase the buoyancy effect. In these cases, however, the flow rate is also influenced by the negative effect of the high viscosity and therefore gives no advantage for the filtration process.

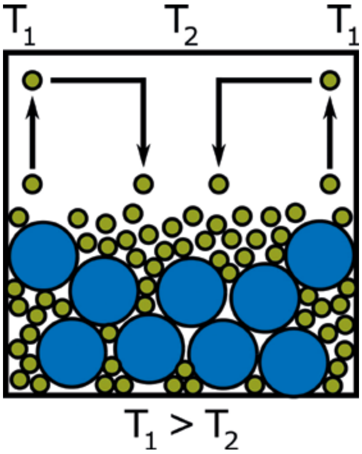

Fig. 10 **Illustration of particle movement because of thermal convection with a high temperature difference between lauter tun wall (T_1) and centre (T_2)**

It is proposed that the buoyancy effect is dependent on thermal convection, based on a temperature difference in the lauter tun (Fig. 10). The temperature of the suspension is constant on the sides due to the insulation of the wall (T_1). However, the temperature can decrease in the upper centre (T_2) where there is no insulation, which means the density increases at this location. The resulting difference in the density can result in a circulating motion of the suspension, similar as described in the literature [10]. As a result, there is an upward flow of particles on the sides and a downward flow in the centre. This movement of the liquid prevents particles from settling, which was observed visually during the experiments. Due to the size of the particles, Brownian motion can be excluded as an explanation of the particle movement [16]. In contrast, if the temperature is generally lower and therefore assumed to be equal at both locations ($T_1 = T_2$), then it is expected that there is no density difference and thus no particle movement and buoyancy. Consequently, the particles can settle at lower temperatures.

4. Conclusions

A high temperature is usually maintained in the lauter tun to increase the flow rate. However, the temperature-dependent viscosity is not the main factor that determines flow rate. It was shown that the filter cake resistance of the fine layer decreases at higher temperatures in addition to the less important viscosity reduction. A buoyancy effect based on thermal convection at high temperatures is responsible for the lower resistance as the particles are hindered from settling, resulting in a lower particle packing of the fine layer. Consequently, blocking of the filter cake is reduced resulting in a higher flow rate.

The results show that high temperatures are essential in lautering to maintain a low resistance of the critical fine particle layer. During the filtration process, however, the temperature cannot be kept constant by heating the lauter tun. Proper temperature insulation of the filter is therefore essential. In addition, temperature losses during the mash transfer should be avoided, e.g. by pumping in the mash from below.

The sedimentation of the fine particles should be avoided for as long as possible during lautering to maintain a low filter cake resistance. This requires a high buoyancy effect. Therefore, the liquid level should not be allowed to decrease to the level of the top of the filter cake during the filtration of the first wort to maintain the buoyancy at the beginning of the second wort.

The buoyancy effect at high temperatures can reduce the resistance of the fine particle layer. Nevertheless, fine particles hinder the filtration process even at high temperatures. In order to avoid the negative effect of fine particles at all, an alternative lautering technique was recently presented in the literature [14], in which the resistance of the top layer was reduced by removing the fine particles prior to the filtration.

The differences in the particle settling of fine and coarse particles at high temperatures affect the structure of the cake. On the one hand, fine particles are hindered from settling and are therefore present at the top in a higher concentration. On the other hand, the settling velocity of coarse particles is increased. This favours the formation of the multilayered filter cake.

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5. References

1. Asselmeyer, F.; Höhn, K.; Issing, E.: Die Temperaturabhängigkeit von Viskosität und Dichte bei Bieren, Ausschlag- und Vorderwürzen, Brauwissenschaft **26** (1973), no. 4, pp. 93-101.
2. Barrett, J.; Clapperton, J. F.; Divers, D. M.; Rennie, H.: Factors affecting wort separation, J Inst Brew **79** (1973), no. 5, pp. 407-413.
3. Bühler, T. M.: Effects of physical parameters in mashing on lautering performance, 1996.
4. Bühler, T. M.; McKechnie, M. T.; Wakeman, R. J.: A model describing the lautering process, Monatsschrift für Brauwissenschaft **7**/**8** (1996), pp. 226-233.
5. Bühler, T. M.; McKechnie, M. T.; Wakeman, R. J.: Temperature induced particle aggregation in mashing and its effect on filtration performance, Food Bioprod Process **74** (1996), no. 4, pp. 207-211.
6. Draxler, J.; Siebenhofer, M.: Verfahrenstechnik in Beispielen, Auflage: Springer Vieweg, 2014.
7. Engstle, J.; Briesen, H.; Först, P.: Mash separation in the lauter tun – a particle size dependent separation process, BrewingScience **70** (2017), pp. 26-30.
8. Evans, D. E.: The Impact of Malt Blending on Lautering Efficiency, Extract Yield, and Wort Fermentability, JASBC **70** (2012), no. 1, pp. 50-54.
9. Gastl, M.; Kupetz, M.; Becker, T.: Determination of Cytolytic Malt Modification – Part II: Impact on Wort Separation, J Am Soc Brew Chem (2020), pp. 1-9.
10. Gotoh, K.; Yamada, S.; Nishimura, T.: Influence of thermal convection on particle behavior in solid-liquid suspensions, Adv Powder Technology **15** (2004), no. 5, pp. 499-514.
11. Greffin, W.; Krauß, G.: Schroten und Läutern. II. Arbeit mit konventioneller Trockenschrotmühle und Läuterbottich – eine Literaturübersicht, Monatsschrift für Brauwissenschaft **31** (1978), no. 6, pp. 192-212.
12. Hennemann, M.; Gastl, M.; Becker, T.: Inhomogeneity in the lauter tun: a chromatographic view, Eur Food Res Technol **245** (2019), pp. 521-533.
13. Hennemann, M.; Gastl, M.; Becker, T.: Influence of particle size uniformity on the filter cake resistance of physically and chemically modified fine particles, Sep Purif Technol **272** (2021), pp. 118966.
14. Hennemann, M.; Gastl, M.; Becker, T.: Optical method for porosity determination to prove the stamp effect in filter cakes, J Food Eng **293** (2021), pp. 110405.
15. Lu, W.-M.; Tung, K.-L.; Pan, C.-H.; Hwang, K.-J.: The Effect of Particle Sedimentation on Gravity Filtration, Sep Sci Technol **33** (1998), no. 12, pp. 1723-1746.
16. Newburgh, R.; Peidle, J.; Rueckner, W.: Einstein, Perrin, and the reality of atoms: 1905 revisited, Am J Phys **74** (2006), no. 6, pp. 478-481.
17. Richardson, J. F.; Zaki, W. N.: The sedimentation of a suspension of uniform spheres under conditions of viscous flow, Chem Eng Sci **3** (1954), no. 2, pp. 65-73.
18. Schaus, O. O.: Elevated temperature lautering, MBAA Tech Q **9** (1972), no. 4, pp. 192-194.
19. Tippmann, J.; Scheuren, H.; Voigt, J.; Sommer, K.: Procedural investigations of the lautering process, Chem Eng Technol **33** (2010), no. 8, pp. 1297-1302.
20. Tippmann, J.; Voigt, J.; Sommer, K.: Measuring particle size distribution of mash with laser diffraction to evaluate the process success, BrewingScience **64** (2011), pp. 13-21.

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